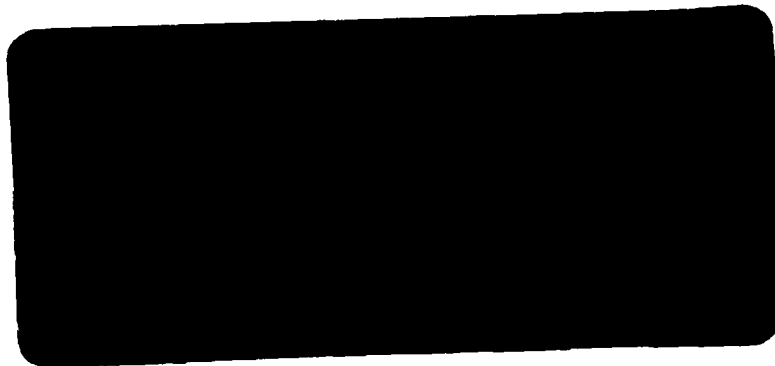


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CALIFORNIA INSTITUTE OF TECHNOLOGY  
PASADENA, CALIFORNIA

# Industrialization Study

PHASE II  
FINAL REPORT

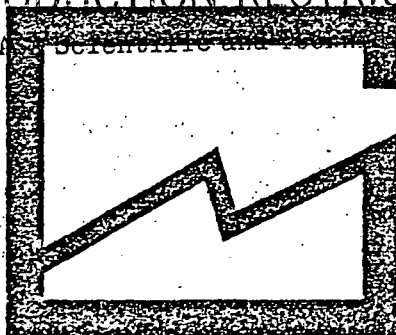
Prepared by  
GNOSTIC CONCEPTS, INC.  
For  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
JET PROPULSION LABORATORY

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The JPL Low-Cost Silicon Solar Array Project is sponsored by the US Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory California Institute of Technology by agreement between NASA and DOE.



## ABSTRACT

This is the final report under Phase II of a program conducted by Gnostic Concepts, Inc. in accordance with Jet Propulsion Laboratory Contract No. 954899, Basic, a subcontract under NASA Contract NAS7-100, Task Order No. RD-152. Management responsibility for this program is within the Low-Cost Solar Array Project on behalf of the US Department of Energy (DOE/ET), Solar Photovoltaic Program. The study was commissioned by the LSA Project Analysis and Integration Manager, Dr. William T. Callaghan, with task force monitoring responsibility under the direction of Dr. Jeffrey L. Smith.

The program described in this final report is an element of the JPL analysis of the industrialization process for the photovoltaic venture. As part of this program, information concerning advanced photovoltaic technologies was collected. Emphasis was placed upon characterizing the present status of these advanced technologies and extracting their future potential capabilities. The ultimate objective was to establish a comparative framework within which selection could be made for government emphasis of high-potential advanced technologies.

Areas covered in this report include the technical assessments of selected advanced technologies. Information collected was in the area of manufacturing process steps and their implications on cell performance, along with present and future expected performance characteristics. In addition, a summary of the technical and manufacturing barriers and a summary of other influences is provided.

A comparative assessment of the advanced technology bases was also constructed. It consists of comparing each of the advanced technologies to the present-day single-crystal silicon wafer technology that dominates commercial activities today and a comparison of the advanced technologies to each other. From this was extracted those technologies that offer the greatest potential for future technology development programs and industrialization efforts.

A rank ordering of the advanced technologies is provided. The various ranking schemes were based upon present-day efficiency levels, their stability and long-term reliability prospects, material availability, capital investments both at the laboratory and production level, and associated variable costs.

A final selection was made of those advanced photovoltaic technologies that have a high potential for industrialization prospects and an estimate of the timing of the possible readiness of these advanced technologies for technology development programs and industrialization. The study culminates in a set of recommended government actions concerning the various advanced technologies addressed in this report.

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# 1. Executive Summary

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## 1.1 INTRODUCTION

### REASON FOR REPORT

This study was driven by the perceived need to evaluate and compare the potentials and requirements of advanced photovoltaic technologies that are still in their early developmental stages. Establishment of such comparative information will be needed in the near future when government agencies attempt to select and develop supportive programs for the technical development and ultimate industrialization of future photovoltaic technologies.

The purpose of this report is thus to provide that framework and rank order these technologies as to their potential for technical and commercial development. In addition, the assessments provide insight into the principal areas of research and developmental efforts needed to produce more favorable technical and economic performance characteristics of these technologies and enhance their probability of industrialization.

### SUBJECT AREAS ADDRESSED

The study addresses the status and potential of advanced photovoltaic technologies based upon the materials of:

- Silicon
- Gallium arsenide
- Cadmium sulfide

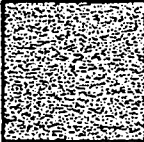
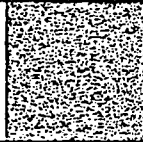
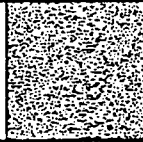
The technologies were further subdivided by the crystalline orientation of the material. This included:

- Single-crystal
- Polycrystalline
- Amorphous

If these six classifications are combined, then a matrix of possible material/crystal orientation technologies can be described as in Figure 1.1. At present, there is a significant multifaceted technology development program in progress under the direction of JPL in the area of single-crystal silicon. For that reason, this particular material/crystalline structure has been excluded from consideration in this contract and report. In addition, the amorphous cadmium sulfide and amorphous gallium arsenide combinations were also excluded from consideration, as there are no presently active industrial or government programs in these areas.

FIGURE 1.1

TECHNOLOGY/ MATERIAL STRUCTURE MATRIX

	Single Crystal	Poly- Crystalline	Amorphous
Silicon			
Gallium Arsenide			
Cadmium Sulfide			



Combinations not under consideration

Since there are investigational activities directed at the single-crystal cadmium sulfide technology option within this matrix, it has also been included in this report. It should be emphasized, however, that the activities in this technology area focus only on obtaining fundamental material and basic mechanism information. They are not pursued in support of the ultimate expectation for industrialization of this technology base. The data provided is thus for completeness only.

Thus the major areas of consideration include:

- Polycrystalline silicon
- Amorphous ( $\alpha$ ) silicon
- Single-crystal gallium arsenide (GaAs)
- Polycrystalline gallium arsenide (GaAs)
- Single-crystal cadmium sulfide (CdS)
- Polycrystalline cadmium sulfide (CdS)

Within the detailed technical assessment discussions, these technologies are also broken down by major cell structures such as P-N junction, Schottky barrier, heterojunction, and p-i-n configurations.

Except for single-crystal GaAs, all of these technologies would be directed at flat-plate applications. The single-crystal GaAs technology has its principal use, however, in concentrator applications due to its costs and unique temperature characteristics.

## 1.2 STUDY RESULTS

The following sections are summary statements of the findings resulting from the study. Supporting details for these findings are not included in this area of the report; they are discussed in the subsequent chapters.

### RANKING OF TECHNOLOGIES--PRESENT-DAY STATUS

#### MATURITY RANKING

The six technology areas emphasized in this report vary tremendously in their state of technical maturity. A ranking of these technologies based on their degree of technical performance, established level of understanding of influences on cell parameters, reproducibility, size of cells, and overall assessment is shown in Table 1.1.

TABLE 1.1  
MATURITY STATUS OF ADVANCED PHOTOVOLTAIC TECHNOLOGIES

Technology	Maturity Status
Single-crystal GaAs*	Well developed
Polycrystalline CdS Polycrystalline Silicon Polycrystalline GaAs	In early stages of development
Amorphous Silicon	In embryonic stage of development
Single-crystal CdS	Undeveloped; pursued only for material and basic mechanism studies

\*Applicable only to concentrator system applications.

The spectrum of technology maturity ranges from that of single-crystal GaAs, which is nearing readiness for pilot production status, to that of single-crystal CdS, which is still a laboratory curiosity.

## EFFICIENCY RANKING

A ranking of the technologies based on present-day efficiency of conversion figures is given in Table 1.2. Again, single-crystal GaAs is significantly beyond the remaining technologies. Except for single-crystal GaAs, the estimated maximum potential efficiencies are all comparable.

TABLE 1.2  
EFFICIENCY RANKING OF ADVANCED PHOTOVOLTAIC TECHNOLOGIES  
(Based on Present-Day Typical)

Rank	Technology	Present-Day Typical (%)	Estimated or Calculated Maximum <sup>1)</sup>
1	Single-crystal GaAs <sup>2)</sup>	20-23	28
2	Single-crystal CdS <sup>3)</sup>	8-12	--
3	Polycrystalline CdS	4-8	13-16
4	Polycrystalline GaAs	6-7	12-14
5	Polycrystalline silicon	3-7	10-14
6	Amorphous silicon	2-6	14-16

1) Except for single-crystal GaAs, none of these are firmly established.

2) Applicable only to concentrator system applications.

3) Included for completeness only; this technology pursued only for material and basic mechanism studies.

## STABILITY AND RELIABILITY RANKING

Based on present-day cell stability and known long-term reliability problem areas, a ranking of the technologies under consideration is presented in Table 1.3. Cells produced by the single-crystal gallium arsenide technology are very stable, and no serious long-term reliability problems are identified. It should be pointed out that no significant level of field testing has been done to support this apparent characteristic.

Polycrystalline silicon and polycrystalline GaAs also appear stable, but they face potential problems due to the existence of grain boundaries. The polycrystalline CdS structures are extremely sensitive to moisture and oxygen. This places severe requirements on packaging. Amorphous silicon cells are presently unstable, especially at the higher efficiency levels and larger cell sizes. So little is known about single-crystal CdS that it was not ranked.

TABLE 1.3

## STABILITY AND RELIABILITY RANKING OF ADVANCED PHOTOVOLTAIC TECHNOLOGIES

Rank	Technology	Comment
1	Single-crystal GaAs	Stable; no serious long-term reliability problems identified.
2	Polycrystalline silicon	Stable; no identified long-term reliability problems; ion migration along grain boundaries may prove to be a problem.
3	Polycrystalline GaAs	Microcracks and pinholes form during growth that may indicate future problems.
4	Polycrystalline CdS	Degrades rapidly when exposed to oxygen and/or moisture; degradation reversible.
5	Amorphous silicon	Instability at higher efficiencies and large-area cells; sensitivity to OH ions.
	Single-crystal CdS	Not ranked due to lack of sufficient data; this technology pursued only for material and basic mechanism studies.

## COMPARATIVE ASSESSMENT OF FUTURE POTENTIALS

The previous assessments were associated with the present-day status of the selected advanced technologies. While each of them face differing sets of problem areas that limit their acceptability today, they all have unique potentials that, once developed, would significantly enhance their possible desirability for industrialization. A comparison of these advanced technologies not only to each other but also to the single-crystal silicon wafer technology base is used to assess the value of these potentials. In addition, the comparisons add insight into the possible criteria for selecting technologies for increased future emphasis.

COMPARISON TO SINGLE-CRYSTAL SILICON

The comparison of the advanced technologies to the single-crystal silicon wafer technology base is presented in Table 1.4. An equal maturity level has been assumed for each technology, and their performance levels are near the expected maximums. The potential characteristics are shown as offering significant advantages or representing serious disadvantages compared to the single-crystal silicon wafer technology base.



TABLE 1.4

ADVANTAGES/DISADVANTAGES OF ADVANCED PHOTOVOLTAIC OPTIONS  
(Compared to Single-Crystal Silicon Wafer Technology Base)

Advantages	Disadvantages	Advantages	Disadvantages
Single-Crystal GaAs		Polycrystalline GaAs	
<ul style="list-style-type: none"> <li>• Response to available insolation is greater</li> <li>• Efficiencies significantly higher</li> <li>• Thinner layers of material required</li> <li>• High-temperature operation possible</li> </ul>	<ul style="list-style-type: none"> <li>• Material costs very high</li> <li>• Material very brittle</li> <li>• Crystal growth processes much slower</li> <li>• Equipment for crystal growth more complex due to high pressures</li> <li>• Higher potential for safety problems due to high pressures and toxicity of As compounds</li> <li>• Supply of Ga could become critical issue</li> </ul>	<ul style="list-style-type: none"> <li>• Growth processes should ultimately be faster and more efficient</li> </ul>	<ul style="list-style-type: none"> <li>• Presence of grain boundaries restricts performance</li> <li>• Quality of structure depends on substrate and interface materials and their preparation</li> <li>• Toxicity of As compounds presents possible hazards</li> <li>• Supply of Ga could become critical issue</li> <li>• Inherent practical efficiency is probably lower</li> <li>• Costs not expected to be lower</li> </ul>
Polycrystalline Silicon		Amorphous Silicon	
<ul style="list-style-type: none"> <li>• Requires less silicon</li> <li>• Potentially lower-cost processing</li> <li>• Applicable to continuous-flow processing</li> </ul>	<ul style="list-style-type: none"> <li>• Presence of grain boundaries restricts performance</li> <li>• Inherent practical efficiency is probably lower</li> </ul>	<ul style="list-style-type: none"> <li>• Lower-cost process</li> <li>• Requires less silicon</li> <li>• Applicable to continuous-flow processing</li> </ul>	<ul style="list-style-type: none"> <li>• Inherent practical efficiency is probably lower</li> <li>• Sensitivity to OH ions requires more stringent packaging</li> </ul>
Single-Crystal CdS*		Polycrystalline CdS	
	<ul style="list-style-type: none"> <li>• Substrate material more expensive</li> <li>• Depends on supply of rare earth elements</li> <li>• Substrates more complex to produce</li> <li>• Toxicity of Cd compounds presents possible hazards</li> </ul>	<ul style="list-style-type: none"> <li>• Lower-cost process</li> <li>• Less complex equipment needed, thus much simpler process steps</li> <li>• Applicable to continuous-flow processing</li> </ul>	<ul style="list-style-type: none"> <li>• Packaging restraints far greater</li> <li>• Toxicity of Cd compounds presents possible hazards</li> <li>• Availability of Cd more restrictive than silicon</li> <li>• Inherent practical efficiency is probably lower</li> <li>• Presence of grain boundaries restricts performance</li> </ul>

\*Included for completeness only; pursued at the laboratory level only for material and basic mechanism studies.

Note the lack of significant advantages of polycrystalline GaAs and single-crystal CdS. The disadvantages of single-crystal GaAs are offset by significant advantages in association with high-temperature concentrator applications. Polycrystalline silicon, amorphous silicon, and polycrystalline CdS offer the best compromise of advantages and disadvantages for direct competition with the single-crystal silicon wafer technology.

#### COMPARATIVE ASSESSMENT OF ADVANCED TECHNOLOGIES

The comparison of the advanced technologies to only themselves is shown in Table 1.5. Again, comparable maturity levels have been assumed. It has also been assumed that packaging concepts to overcome any identified impacts from the environment are possible. This does not necessarily mean they are inexpensive, just technically feasible.

Amorphous silicon stands out in this comparison as having the most desirable set of cost/performance characteristics. This is in contrast to its present-day status, in which it is one of the least developed and poorest performers in the photovoltaic area. Polycrystalline silicon and polycrystalline CdS also have excellent cost prospects but are limited by grain boundaries, substrate materials, and possible reliability problems.

#### SUMMARY OF MAJOR BARRIERS TO RESOLVE

Each of the advanced technology options is limited in its present status by technical and manufacturing barriers that must be resolved if their potential cost/performance characteristics are to be maximized. In addition, there are other influences that could alter the development pace and prospective value of a technology either positively or negatively. The following is a summary of those barriers and other influences associated with each of the advanced technology bases addressed in this report.

TABLE 1.5

## COMPARATIVE ASSESSMENT OF ADVANCED PHOTOVOLTAIC TECHNOLOGY OPTIONS

Technology Base	Advantages	Disadvantages
Single-crystal GaAs	<ul style="list-style-type: none"> <li>• Highest practical and theoretical efficiency</li> <li>• Not influenced by grain boundaries as in polycrystalline-based technologies</li> <li>• High-temperature operation possible</li> </ul>	<ul style="list-style-type: none"> <li>• Costs limit application to concentrator systems</li> <li>• Greater toxicity problems than for silicon or CdS technologies</li> <li>• Processing not easily converted to continuous-flow methods</li> <li>• Ga supply potential problem area</li> </ul>
Polycrystalline GaAs	<ul style="list-style-type: none"> <li>• Slightly higher potential for efficiency than for polycrystalline silicon and CdS</li> <li>• Processing adaptable to continuous-flow methods</li> </ul>	<ul style="list-style-type: none"> <li>• Higher costs than polycrystalline silicon for limited increase in efficiency</li> <li>• Heavy influence of substrate and interface material on film quality and characteristics</li> <li>• Greater toxicity problems than for silicon and CdS technologies</li> <li>• Characteristics heavily influenced by grain structure</li> <li>• Ga supply potential problem</li> </ul>
Polycrystalline silicon	<ul style="list-style-type: none"> <li>• Material availability better than for polycrystalline GaAs and CdS</li> <li>• Material cost reductions of single-crystal silicon programs directly applicable; not so for GaAs or CdS</li> <li>• Process adaptable to continuous-flow methods</li> </ul>	<ul style="list-style-type: none"> <li>• Heavy influence of substrate and interface material on film quality and characteristics</li> <li>• Characteristics heavily influenced by grain structure</li> </ul>
Amorphous silicon	<ul style="list-style-type: none"> <li>• Film quality and growth not dependent on substrate materials</li> <li>• Material availability excellent</li> <li>• Efficiency potential as good as any thin-film technology base</li> <li>• Applicable to continuous-flow processing steps</li> <li>• Potential for lowest cost of thin-film processes</li> <li>• No grain boundaries to influence film characteristics</li> <li>• Material cost reductions of single-crystal silicon programs directly applicable</li> </ul>	<ul style="list-style-type: none"> <li>• Sensitive to OH ions, implies higher-cost packaging than for polycrystalline silicon</li> </ul>
Single-crystal CdS*	<ul style="list-style-type: none"> <li>• Cell performance not influenced by grain size or grain boundaries as in polycrystalline structures</li> </ul>	<ul style="list-style-type: none"> <li>• Depends upon very expensive substrate materials, elements of which are limited in availability</li> <li>• Performance limited by substrate material quality</li> <li>• Processing not easily converted to continuous-flow process</li> </ul>
Polycrystalline CdS	<ul style="list-style-type: none"> <li>• Potential for low-cost, thin-film processing methods</li> <li>• Process uses modified off-the-shelf equipment</li> <li>• Probably the simplest processing</li> </ul>	<ul style="list-style-type: none"> <li>• Cell parameters influenced by grain structure</li> <li>• Severe sensitivity to oxygen and moisture, requires more stringent packaging than polycrystalline silicon and GaAs</li> <li>• Availability of cadmium more restrictive than silicon</li> </ul>

\*Included for completeness only; this technology pursued only at laboratory level for material and basic mechanism studies.

## POLYCRYSTALLINE SILICON

### TECHNICAL BARRIERS

The following major technical barriers must be resolved before any optimization or scale-up of selected cell structures can be anticipated:

- Lack of understanding of grain boundary effects
  - Limitation on efficiency
  - Characterization of growth conditions for large-grain-sized material
  - Influence of substrate material on grain size
- Unknown effects of impurities from substrate and silicon materials
- Selection of adequate substrate material
- Selection of cell structure and associated materials such as dopants for P-N junctions and appropriate interface material for heterojunctions
- Lack of understanding of limitations on carrier lifetimes

### MANUFACTURING BARRIERS

Once technical feasibility has been demonstrated, certain manufacturing limitations must be overcome. They include:

- Selection and optimization of large-scale deposition process equipment
- Optimization of cell structure
- Functional integration of cell structure and packaging materials
- Establishment of proper process, quality, and environmental controls

### OTHER RELATED INFLUENCES TO COMMERCIALIZATION

There are other influences that could affect the development pace of this technology base in either positive or negative fashion. These areas of influence include:

- Determination of long-term field reliability
- Nature of continued government support contracts

- Development pace of amorphous silicon and other thin-film technologies
- Level of resources devoted to research and development activities in this technical area

## AMORPHOUS SILICON

### TECHNOLOGY BARRIERS

The following technical barriers must be successfully addressed before a large-scale development program is warranted:

- Need to develop and understand models and the associated quantum theory of amorphous structures
- Determine which of the amorphous silicon deposition methods offer best large-scale, continuous-flow potential
- Characterization of basic mechanisms:
  - Deposition and growth conditions for amorphous silicon
  - Dopants and doping techniques
  - Carrier lifetimes
  - Ohmic contact
  - Effect of bulk  $\alpha$ -silicon series resistance
  - Effect of hydrogen during silicon growth
  - Sensitivity to OH ions and its implications
- Scale-up of laboratory equipment associated with silicon deposition to facilitate investigation of large-cell-area-related problems

### MANUFACTURING BARRIERS

Upon establishment of a solidified technology base, the following manufacturing barriers will need resolution

- Innovation in device structures; must depart from single-crystal analogies to produce functionally integrated devices and packages
- Develop source of inexpensive silane; possible solution is contained in Union Carbide's polysilicon plant design
- Scale-up of selected process and device structure will require development of low-maintenance equipment associated with:
  - Vacuum interlocks
  - Handling of large sheets (4' X 4' minimum)
  - Silicon deposition
  - Other material deposition

- Development of safety precautions as silane is pyrophoric
- Development of appropriate quality control procedures

#### OTHER RELATED INFLUENCES TO COMMERCIALIZATION

The following items could have an influence on the ultimate deployment of amorphous silicon:

- Long-term reliability unknown; industry sources feel that latent failure modes are unlikely, but only through extensive field testing can it be assured
- Cost/performance characteristics of polycrystalline silicon and its development pace
- Confidence in long-term market development; without it there will be limited incentive to pursue research and development programs

#### SINGLE-CRYSTAL GaAs

##### TECHNOLOGY BARRIERS

The following is a summary of the major technology barriers that must be resolved before large-scale industrialization can be possible:

- Determine quantitatively the best epitaxial deposition method; options include vapor phase, liquid phase, and metal organic approaches
- Cost reduction of GaAs substrate material; may require similar cost reduction program as for present-day single-crystal silicon
- Optimization of structures required
  - Doping and defect mechanisms are not fully understood or characterized
  - Improvement in minority carrier lifetime
  - Improvement needed in series resistance of metal grid contacts
- Industry sources indicate higher efficiencies are needed if bulk energy markets are to be supplied; need development of advanced systems such as high-efficiency cascade or multijunction cells

## MANUFACTURING BARRIERS

A scaling up of the present laboratory processes will require efforts devoted to:

- Development of specialized handling equipment due to the brittle nature of GaAs material
- Development of large-scale epitaxial equipment once technology issue is resolved
- Establishment of process and quality control methods to ensure reproducibility and uniformity
- Establishment of specialized controls to account for the toxic nature of arsenic compounds

## OTHER RELATED INFLUENCES TO COMMERCIALIZATION

There are other issues that could influence the development pace of single-crystal GaAs devices both positively and negatively. These include:

- Material availability, especially gallium; is thought to be sufficient, but must be quantitatively confirmed
- Field reliability data is lacking; data is insufficient to confirm or deny existence of long-term latent failure modes
- Development pace of low-cost, high-concentration ratio collect designs
- Lack of multiyear government contracts can limit industry's capital commitment to single-crystal GaAs production scale-up efforts
- Availability of commercial markets willing to accept concentrator systems; to date only government contracts make up the market

## POLYCRYSTALLINE GaAs

### TECHNICAL BARRIERS

The following fundamental technical barriers must be resolved before a scaling-up of laboratory processes is applicable:

- Selection and characterization of compatible substrate materials
- Selection of proper substrate interface material and its growth conditions
- Selection of GaAs layer growth process; need to develop process to grow 15 to 20  $\mu\text{m}$  grain size with 5 to 10  $\mu\text{m}$  film thickness

- Identification of inherent failure modes
- General understanding of basic mechanisms associated with the growth, control, and electrical contact of polycrystalline structures

MANUFACTURING BARRIERS Little can be constructively stated at this point concerning potential manufacturing barriers, since the process details are not even remotely finalized or reduced to a limited set of options. In general, they will be associated with:

- Cost reduction and supply of gallium, arsenic, and substrate material
- Safety standards
- Equipment scale-up of layer growth and deposition chambers
- Low cost metal grid process
- Package and cell functional integration

OTHER RELATED INFLUENCES TO COMMERCIALIZATION Development of this technology base can be influenced either negatively or positively by other related influences. These would include:

- Development pace and ultimate cost/performance characteristics of polycrystalline silicon cells
- Nature of inherent reliability failure modes and the impact of the environment upon them
- At present, a limited number of persons and companies are involved in this technology base and its development; this could limit ultimate development pace

#### SINGLE-CRYSTAL CdS

TECHNICAL BARRIERS  
barriers include:

The present identified technical

- Need for better understanding of photovoltaic effect
  - Heterojunctions in general
  - InP/CdS and CdTe/CdS in particular
- Improvement in quality and understanding of junction interface area



- Development of doping techniques and characterization of dopant effects
- Identification of impact of substrate material characteristics
- General reduction in material defect levels
- Nonrepeatability of laboratory processes

With continued development of cell knowledge, other more focused technical barriers will be identified.

#### MANUFACTURING BARRIERS

The present state of development of this technology base has not required serious concern over manufacturing barriers. In fact, no serious attempts at commercial development are contemplated. This technology has been and will continue to be pursued for the purpose of obtaining material and basic operating mechanism information.

#### POLYCRYSTALLINE CdS

#### TECHNICAL BARRIERS

The following technical issues must be resolved before industrialization of sufficiently high-efficiency cells can be implemented:

- Selection of basic device process
  - Substrate material
  - Layer deposition method
    - Vacuum
    - Dipping
    - Sputtering
    - Spraying
- Doping techniques and influence of dopants
- Optimizing grain boundary composition
- Develop low-cost metal grid system and its proper ohmic contact characteristics
- Development of hermetic package and associated manufacturing techniques

#### MANUFACTURING BARRIERS

Once the basic technical barriers are resolved and sufficient understanding of the processes are established, the scale-up in manufacturing equipment and techniques will evolve as a critical issue. The present identifiable areas needing attention that are common to the various available processes include:

- Control of cadmium emissions
- Control of waste etch and plating solutions
- Identification of manufacturing parameters that influence reproducibility

Depending upon which basic device process is selected, there could be equipment development problems in the areas of:

- Continuous-flow vacuum and sputtering deposition equipment
- Layer thickness control monitors
- General process control equipment

#### OTHER RELATED INFLUENCES TO COMMERCIALIZATION

There are other items that could influence the development rate of the CdS/Cu<sub>2</sub>S processes both positively and negatively. These would include:

- Establishment of long-term field reliability data
- Application of present JPL programs
  - Encapsulation
  - Metal grid structures
  - Packaging materials
  - Continuous-flow vacuum deposition
- Commercial availability of cadmium

### 1.3 INTERPRETATION OF STUDY RESULTS

#### FUTURE POTENTIAL FOR INDUSTRIALIZATION

Review of the characteristics of the advanced technologies under consideration shows a distribution of the potential for industrialization. By industrialization is meant the widespread adoption of low-cost manufacturing processes and techniques associated with a photovoltaic technology base. The principal criteria for industrialization would be:

- Prospects of low-cost production
- Prospects of acceptable performance characteristics
- Prospects of a large market demand

None of the advanced technologies presently meet these criteria sufficiently to justify an industrialization program for any of them.

With sufficient technical improvement within the laboratory environment, followed by a successful technology development program, there are selected ones of the advanced technologies that hold a higher potential for industrialization. Assuming that technical performance is reproducibly demonstrated in the laboratory environment and a successful technology development program has been completed, the advanced technologies that hold the higher prospects for industrialization are highlighted in Table 1.6.

The polycrystalline silicon, polycrystalline cadmium sulfide, and amorphous silicon technologies all hold prospects for low-cost production and acceptable performance characteristics. These three technologies would be directed toward flat-plate applications and the market for such applications has been assumed sufficient to justify industrialization.

The single-crystal gallium arsenide technology, while meeting the criteria for acceptable performance characteristics, can only meet the cost requirements for industrialization if it is directed toward concentrator applications. This would also include hybrid systems. In this case, industrialization prospects would be limited due to the perceived commercial application limitations in the predictable future (maximum of ten years). Industrialization would thus depend on the degree of identified concentrator application areas and their market potential. Because of these perceived limitations, the potential for industrialization of a single-crystal gallium arsenide process is lower than for the previously mentioned three technologies. While the prospects are lower, this does not mean that it should not be given serious consideration.

TABLE 1.6  
FUTURE POTENTIAL FOR INDUSTRIALIZATION\*

Potential	Technology Base	Comments
High	Polycrystalline silicon Polycrystalline CdS Amorphous silicon	These all represent very low-cost potentials; if performance and reliability can be demonstrated, then industrialization is highly possible.
Possible but with difficulty	Single-crystal GaAs	Widespread industrialization will be limited due to perceived commercial application limitations in predictable future (maximum of next ten years); will depend on degree of identified concentrator application areas and their potential.
Low	Polycrystalline GaAs	Even if excellent performance and reliability characteristics are demonstrated, cost-performance trade-offs will restrict industrialization.

\*Assumes: Performance characteristics can be reproducibly demonstrated; reliability can be established.

The polycrystalline gallium arsenide technology base does not appear to offer the necessary cost advantages to encourage industrialization. While performance and reliability characteristics can possibly be demonstrated in the future, the cost/performance trade-offs will be restrictive.

The single-crystal CdS technology base was not included in the above assessment, as this technology is pursued strictly for material and basic mechanism studies. It will thus remain in the laboratory environment.

#### TECHNOLOGIES APPLICABLE FOR TECHNOLOGY DEVELOPMENT

The intended development sequence of a technology base includes:

- Feasibility demonstration
- Technology development
- Industrialization

The feasibility demonstration phase is concerned with laboratory demonstrations that establish the existence of the photovoltaic effect in a given material combination and structure. The reproducibility and stability characteristics of the structure are also key elements of the development phase. Optimization of the structures or processes is often lacking at this stage, however.

Within the technology development step, programs are implemented that are directed at such items as solidification of cell structures, characterization of cell parameters, package development, optimization of cost parameters, and process documentation. This phase of development will most likely require three to five years for completion.

None of the advanced technologies addressed in this report are beyond the feasibility demonstration stage at the present time. There are, however, significant differences in the state of development among these technologies as related to performance, reproducibility, and stability. An assessment of the minimum time required to prepare these technologies for a technology development program is shown in Table 1.7.

TABLE 1.7  
MINIMUM TIME REQUIRED BEFORE TECHNOLOGY COULD BE READY\*  
FOR TECHNOLOGY DEVELOPMENT PROGRAM

Minimum Time Required	Technology Base	Comment
<2 years	Single-crystal GaAs	Close to full potential now
2-5 Years	Polycrystalline CdS	Reliability problems would have to be overcome
>5 Years	Polycrystalline silicon Polycrystalline GaAs Amorphous silicon	In general, reliability, reproducibility, costs, and performance significantly below estimated potential; lack of sufficient understanding, not sufficiently developed to justify technology development program presently.

\*Refers to reproducibly demonstrating performance characteristics.

Single-crystal gallium arsenide is by far the most developed, mature, and stable of the advanced technologies. In selected facilities it is ready for pilot-line production status. Based on this, the probabilities would be quite high that a technology development program could be justified and implemented within the next one to two years.

Polycrystalline cadmium sulfide will require two to five years more development before beginning a technology development program. The reliability problems commonly associated with this technology would have to be overcome and may ultimately be the downfall of this technology. Nonetheless, significant advances are being made in the laboratory environment to increase the efficiency and reproducibility of this technology base.

Those technologies that are not likely to be ready for a technology development program within the next five years include polycrystalline silicon, amorphous silicon, and polycrystalline gallium arsenide. In general, reliability, reproducibility, cost, and performance are significantly below estimated potentials. In addition, there is a lack of sufficient understanding of the specific mechanisms operating within the cell structures. These technologies are not likely to be sufficiently developed to justify a technology development program within the next five years, especially if left to develop on their own with the present level of resources devoted to them. A technological breakthrough or a sudden resolution of critical barriers could, however, alter the assessment of these long-range technologies significantly.

#### CRITERIA FOR CONSIDERING A TECHNOLOGY DEVELOPMENT PROGRAM

It would not be wise to expend funds and resources on a technology development program for an advanced technology if certain minimum criteria had not already been met within the laboratory environment. The principal criteria that could be used for establishing the maturity level of an advanced technology and for measuring its readiness for a widespread technology development program are based primarily upon:

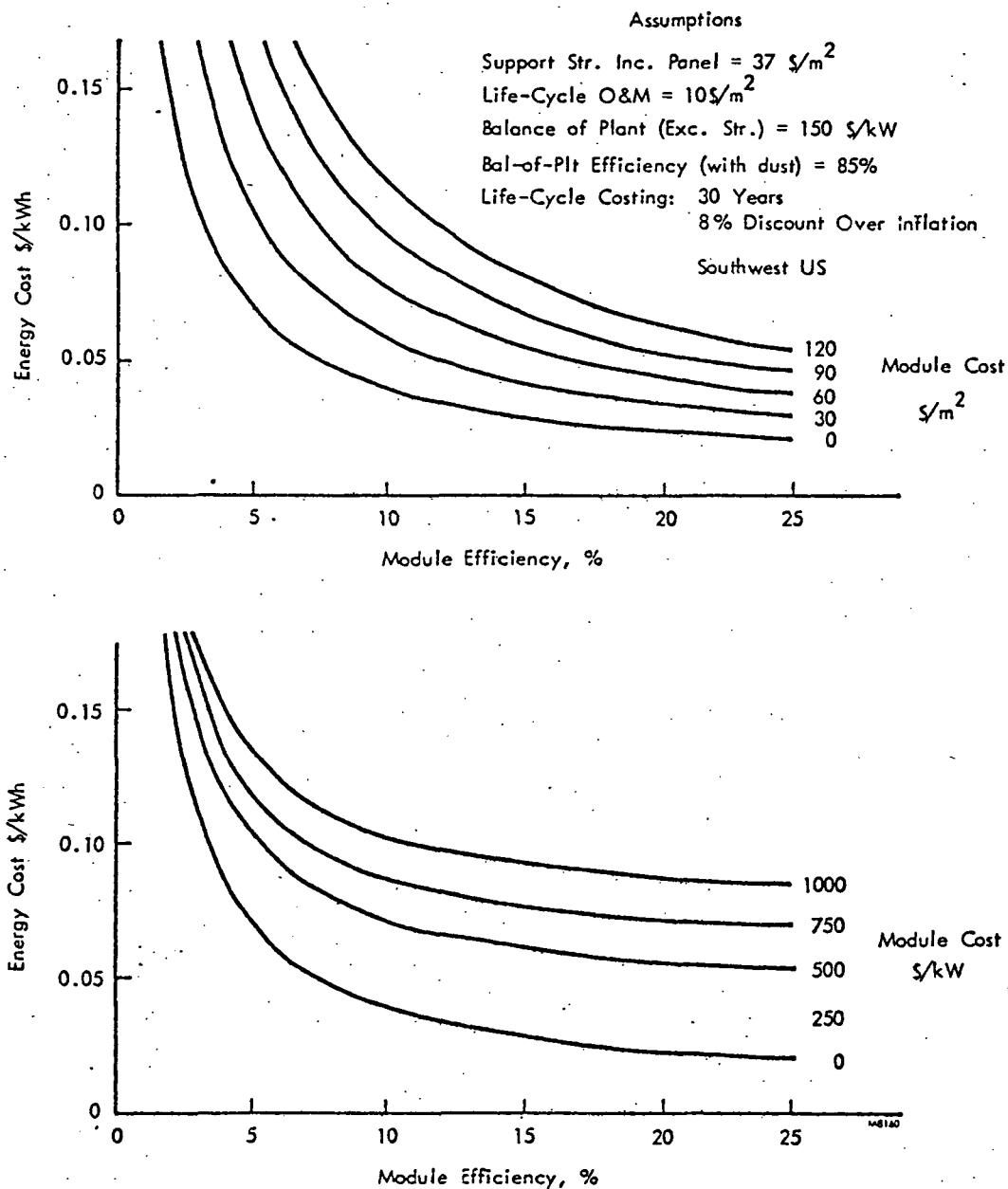
- Efficiency of conversion
- Reproducibility
- Stability and reliability

## EFFICIENCY OF CONVERSION

Laboratory samples of an advanced technology should have efficiency of conversion levels of at least 10 percent, preferably higher. This is based generally on the accepted position that if efficiency is below 10 percent, the balance of the system costs will be prohibitive. Reference should be made to Figure 1.2.

FIGURE 1.2

### PHOTOVOLTAIC ENERGY COST VS. MODULE COST AND EFFICIENCY



Source: JPL

## REPRODUCIBILITY

The reproducibility of an advanced technology in the laboratory environment can be judged on the yields that are obtained in various laboratory runs. Yields to functional devices as well as yields to a prescribed set of parameter specifications can give different insights. If the number of nonfunctional cells is high, then there is question as to the validity and reliability of the remaining functional cells. If the loss due to functionality is very low, then reasonable assurance can be placed in the reproducibility of the technology.

The distribution of the cell parameters can be bell-shaped, with a wide distribution or a very narrow distribution. The more narrow the distribution, the more confidence can be placed in the reproducibility of the product. The distribution can also be truncated, hopefully to the desirable side of the parameter. When such a truncation exists, it generally indicates that the bulk of the material is near the inherent maximum capability of that particular process and structure.

A second aspect to reproducibility is whether or not the process can be sufficiently documented to allow others to produce similar results. This tends to separate out those areas associated with the "art" of the process or specific techniques required for reproducibility and those areas that are fundamentally sound and based on reproducible scientific premises.

## STABILITY AND RELIABILITY

Two basic criteria in this area should be applied to an advanced technology before moving it into a technology development program. First is the identification of cell sensitivity to moisture, oxygen, temperature, and air in its unpackaged form within the laboratory environment. These sensitivity tests will indicate the type of packaging requirements that will be placed upon this technology for successful long-term reliability.

The second criterion is the need for actual field data for at least one full year. This allows exposure of the product in its completed package form to a complete annual weather cycle. The intent here is to identify degradation modes caused by loading conditions, insolation conditions, moisture, and other environmental influences.



## RECOMMENDED GOVERNMENT ACTION

It is assumed that resources in both economic and manpower categories are insufficient to support simultaneous high-emphasis programs in all of the advanced technology areas. Thus a selection should be made as to where government emphasis should be placed. Those technology areas that offer the best near-term, intermediate-term, and long-term prospects should receive the highest emphasis. All other technology areas should be pursued, but at a lower level of emphasis. The recommended government actions are shown in Table 1.8.

TABLE 1.8  
RECOMMENDATIONS FOR GOVERNMENT DEVELOPMENT EMPHASIS

Recommendation	Technology Base (Recommended Government Action)	Comments
Recommended for government emphasis	Single-crystal GaAs (technology develop- ment program)	Most mature; offers best potential in concentrator applications
	Polycrystalline silicon (contracts to support laboratory feasibility demonstrations)	Best available thin-film alternative to single-crystal sheet or ribbon for low-cost, continuous-flow processing; performance potential comparable to polycrystalline CdS without potential reliability problems
	Amorphous silicon (contracts to support laboratory feasibility demonstrations)	Best long-term potential for costs; excellent material availability; technology under- standing applicable to many other application areas and materials
Possible as alternative to polycrystalline silicon	Polycrystalline CdS (contracts to support laboratory feasibility demonstrations)	Best presently-developed thin- film technology base; proper packaging could overcome reliability problems; material availability not as good as silicon; however, could offer quicker thin-film solution than polycrystalline silicon.
Not recommended as primary governmental emphasis	Polycrystalline GaAs Single-crystal CdS	Continue investigations at laboratory level for pursuit of material and basic mechanism studies

Recommended for government emphasis is the completion of the technology development program for single-crystal gallium arsenide. This program is already well underway through the government Sandia Laboratory facilities. This technology option is the most mature and offers the best potential in concentrator applications. It should be developed to its fullest potential to ensure its readiness for future concentrator markets.

For the intermediate time frame requirements, the polycrystalline silicon technology should now become a major government emphasis. Emphasis here would be in the form of support contracts for demonstrating laboratory feasibility. Polycrystalline silicon is the best available thin-film alternative to single-crystal sheet or ribbon technology for low-cost continuous-flow processing. Its potential performance levels are comparable to polycrystalline cadmium sulfide without the potential reliability problems.

A possible alternative to polycrystalline silicon is the polycrystalline cadmium sulfide technology base. Again, emphasis here would be on establishing laboratory feasibility demonstrations. Polycrystalline cadmium sulfide is better developed at the present time than polycrystalline silicon. It does have a history of reliability problems, and its material availability has not been sufficiently verified. It could, however, offer a quicker thin-film solution than polycrystalline silicon.

The final area of major government emphasis should be upon the amorphous silicon technology base. This offers the best long-term (ten years and beyond) potential for costs, material availability, and performance criteria, even over thin-film sheets of single-crystal silicon.

The polycrystalline gallium arsenide and single-crystal cadmium sulfide are technologies that should not be emphasized at the present time. They have very limited inherent advantages which are offset by high costs and a lack of superior performance potential compared to other advanced technology options. It is recommended that these and any future identified advanced technologies be supported, but at a much reduced level in terms of funds and manpower.

There will always be advanced technologies being brought to the attention of the photovoltaic industry. All should be pursued in hopes that a superior technology base will be identified that will meet all of the economic, performance, and market criteria for a successful photovoltaic venture. There must be, however, a judicious selection of those options that attract the major emphasis of available resources.

## 2. Study Objectives

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### 2.1 STATEMENT OF PURPOSE

In Phase I of the INDUSTRIALIZATION STUDY, the emphasis was placed upon understanding the industrial investment decision-making environment and the government's potential influence upon it, in relationship to viable present-day photovoltaic technologies and their implementation. Phase II of the study places the emphasis upon the assessment of advanced photovoltaic technologies and their potential for commercialization.

Through a thorough comparison of the various advanced technologies, the appropriate government organizations will be better able to select, prioritize, or schedule proper support programs for these technologies as industrialization conditions or objectives so warrant. The purpose of this report is thus to provide that comparative framework and rank order those technologies as to their likelihood of commercialization. In addition, the assessments indicate the principal areas of needed research and developmental efforts to cause more favorable technical conditions for the feasibility of commercialization.

## 2.2 TASK DESCRIPTIONS

This study was directed at the assessment of problems associated with the industrialization of selected advanced photovoltaic technologies. The pursuit of the objectives was divided into three basic task functions. A description of those tasks is as follows:

### TASK I--TECHNOLOGY ASSESSMENT/LITERATURE SURVEY

- Evaluate alternative cell technologies under consideration for advanced photovoltaic technology options in the areas of:
  - Silicon
    - Polycrystalline
    - Amorphous
  - Gallium arsenide
    - Single-crystal
    - Polycrystalline
    - Amorphous
  - Cadmium sulfide
    - Single-crystal
    - Polycrystalline
- Evaluate the following characteristics of these cell technologies to include:
  - Technology performance characteristics
    - Stability
    - Short circuit current
    - Open circuit voltage
    - Fill factor
  - State of the technology
    - Efficiency (present versus theoretical)
    - Maturity (laboratory/production)
  - Commentary on collateral technology requirements or factors influencing long-term prospects
    - Encapsulation
    - Packaging
    - Interconnect
    - Environmental

## TASK 2--INDUSTRIALIZATION ASSESSMENTS

- Develop information which will allow the comparison of alternative advanced technologies as they impact ultimate industrialization
  - Strengths or potential advantages
  - Weaknesses or inherent limitations
  - Supply of base material
  - Relative capital investment requirements
  - Relative variable cost opportunities
  - The industrialization base:
    - Active companies
    - Government laboratories
    - Universities
    - Research institutes

## TASK 3--INDUSTRIALIZATION ALTERNATIVE RANKINGS

As a result of Tasks 1 and 2, prepare a ranking of different advanced technologies from an industrialization view. It is to indicate technologies that represent:

- A high potential for industrialization
- Possible industrialization, but with difficulty
- High-risk options

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### 3. Technology Assessments

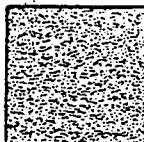
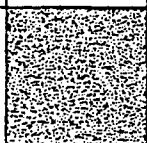
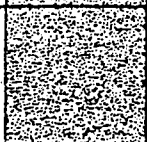
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#### 3.1 INTRODUCTION

##### OBJECTIVE

This section of the report concerns itself with the assessment of the various advanced photovoltaic technologies. The technology options emphasized are shown in Figure 3.1.

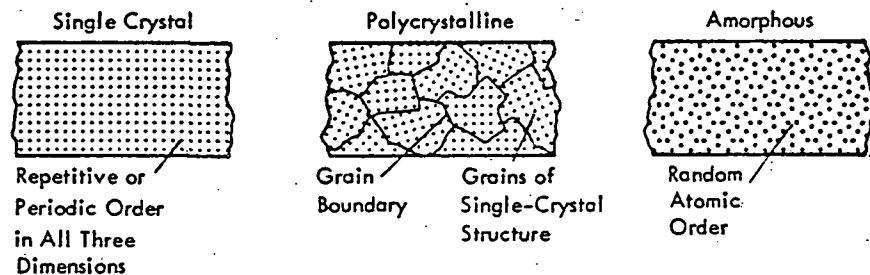
FIGURE 3.1  
TECHNOLOGY/ MATERIAL STRUCTURE MATRIX

	Single Crystal	Poly- Crystalline	Amorphous
Silicon			
Gallium Arsenide			
Cadmium Sulfide			

 Combinations not under consideration

The technologies are distinguished not only by basic material type, but also by crystalline orientation--single-crystal, polycrystalline, and amorphous. A simplistic perspective of the material crystalline orientation is shown in Figure 3.2.

FIGURE 3.2  
DESCRIPTIVE NATURE OF MATERIAL STRUCTURES



Certain technology options have been excluded from the possible matrix of material type and crystalline orientation. The single-crystal silicon cell is not considered one of the "advanced" technologies. This technology base is well-established and -documented. At the present time, there is a significant effort in progress under the direction of the Jet Propulsion Laboratory to optimize and encourage industrialization of this technology base.

The amorphous cadmium sulfide option has also been excluded from consideration, as there are no presently active development programs in this area. The same can be said for the amorphous gallium arsenide option. There are fundamental investigations into amorphous materials; but except for silicon, none have been applied or have resulted in photovoltaic device structures.

## DEFINITIONS

There are several commonly-used parameters to describe and compare photovoltaic cell performance characteristics. The most common are:

- $V_{OC}$ --open circuit voltage

That voltage generated across the terminals of a photovoltaic device under illumination and an open-circuit load condition



- $J_{SC}$ --short-circuit current density

That current produced per unit area of the photovoltaic device under illumination and having a short-circuit load across its terminals

- FF--fill factor

A measure of the quality of the diode characteristics; quantitative comparison to ideal diode performance

- $\eta$ --Efficiency

The effectiveness of converting incident energy to available output power

The interrelationship of these parameters is shown in the following equation:

$$\eta = \frac{(J_{SC}) (V_{OC}) (FF)}{\text{Incident Energy}}$$

The application of these parameters to photovoltaic cell current-voltage output characteristics is shown in Figure 3.3, where:

- $P_M$  = maximum power output condition
- $J_{MP}$  = current density when cell is operating at maximum power output conditions
- $V_{MP}$  = output voltage when cell is operating at maximum power output conditions

The quantitative definition of FF is:

$$FF = \frac{(J_{MP}) (V_{MP})}{(J_{SC}) (V_{OC})}$$

The fill factor is thus a comparison of the cell characteristics to those of the ideal cell.

Variations in these parameters and their influence upon the current-voltage characteristics are shown in Figures 3.4, 3.5, and 3.6. These basic parameters and the items influencing them will be discussed for each of the material/crystalline structure combinations that follow. The parameter most emphasized will be efficiency ( $\eta$ ). It is the most revealing parameter as to the influence of the cell characteristics upon system economic viability.

FIGURE 3.3  
PHOTOVOLTAIC CELL CURRENT-VOLTAGE CHARACTERISTICS

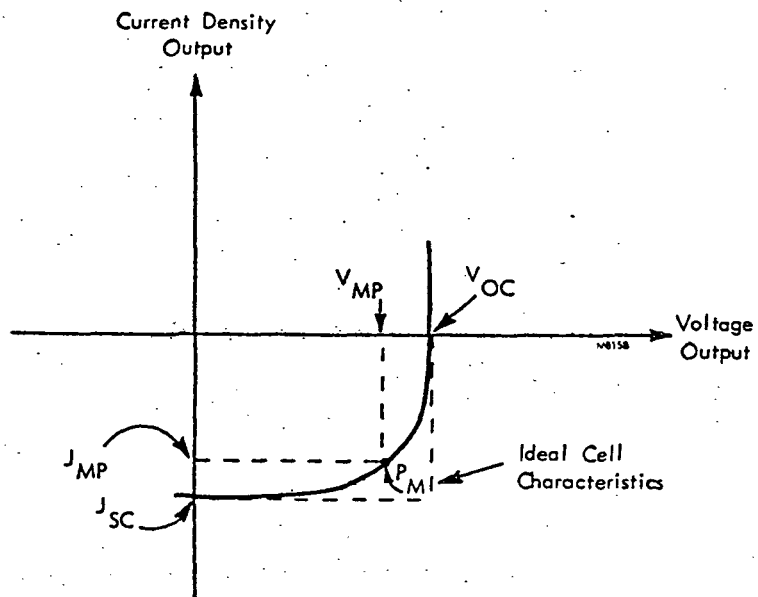


FIGURE 3.4  
VARIATION OF  $V_{OC}$ ,  $J_{SC}$ , AND  $P_M$  FOR FIXED FF

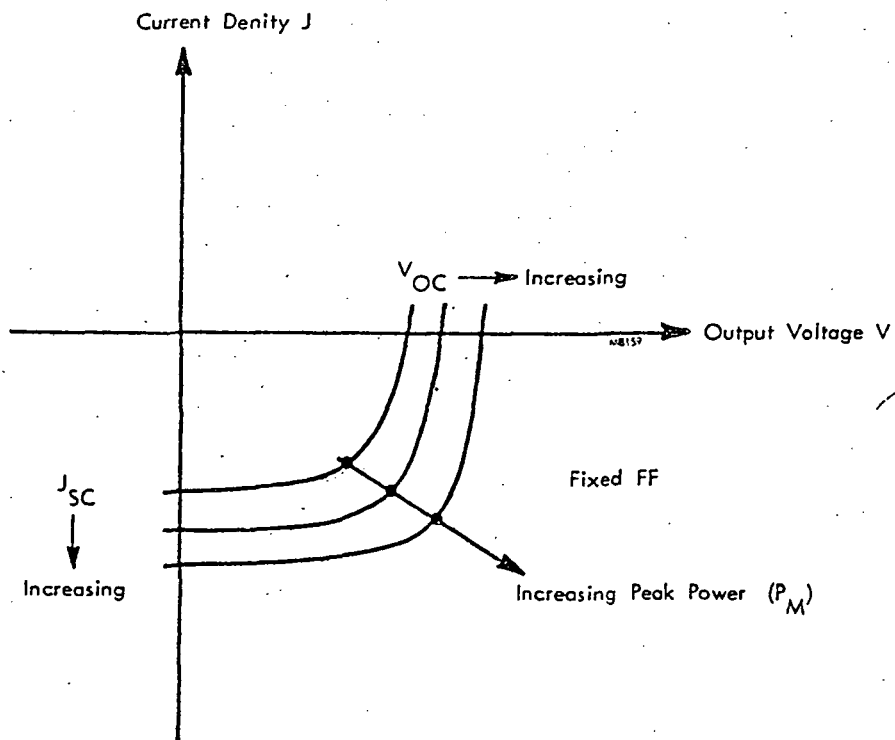


FIGURE 3.5  
VARIATION IN FF AND  $P_M$  WITH FIXED  $V_{OC}$  AND  $J_{SC}$

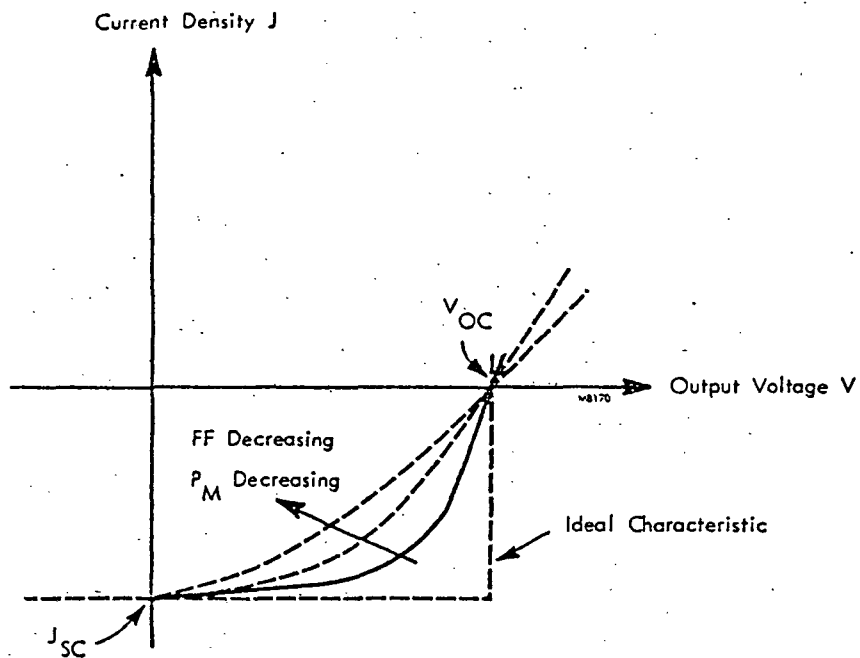
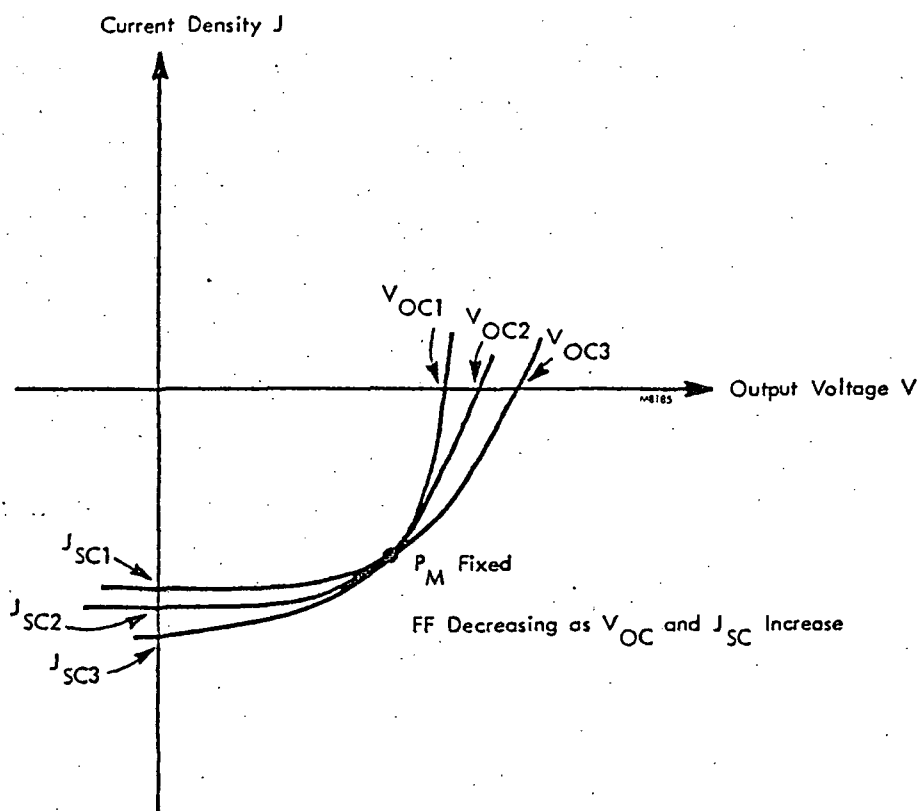
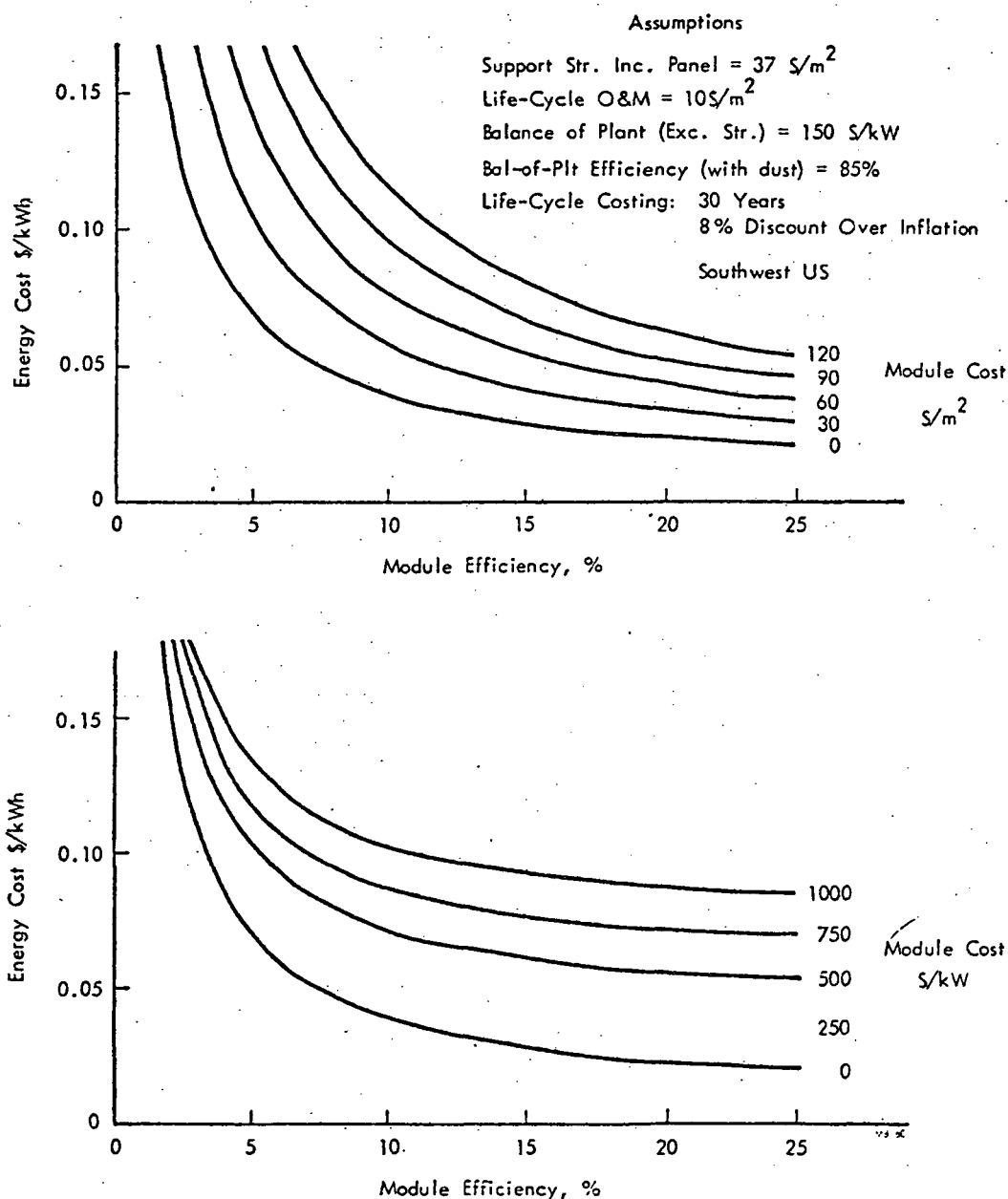


FIGURE 2.4  
VARIATION OF FF WITH INCREASING  $V_{OC}$  AND  $J_{SC}$  AND FIXED  $P_M$



The effect of cell efficiency on energy costs is demonstrated in Figure 3.7. Here energy cost is shown as a function of module or cell efficiency for a specific set of system conditions. Note the heavy influence of cell efficiency on energy costs for efficiencies below 10 percent. These curves should be kept in mind when reviewing the performance data presented in the following sections.

FIGURE 3.7  
PHOTOVOLTAIC ENERGY COST VS. MODULE COST AND EFFICIENCY

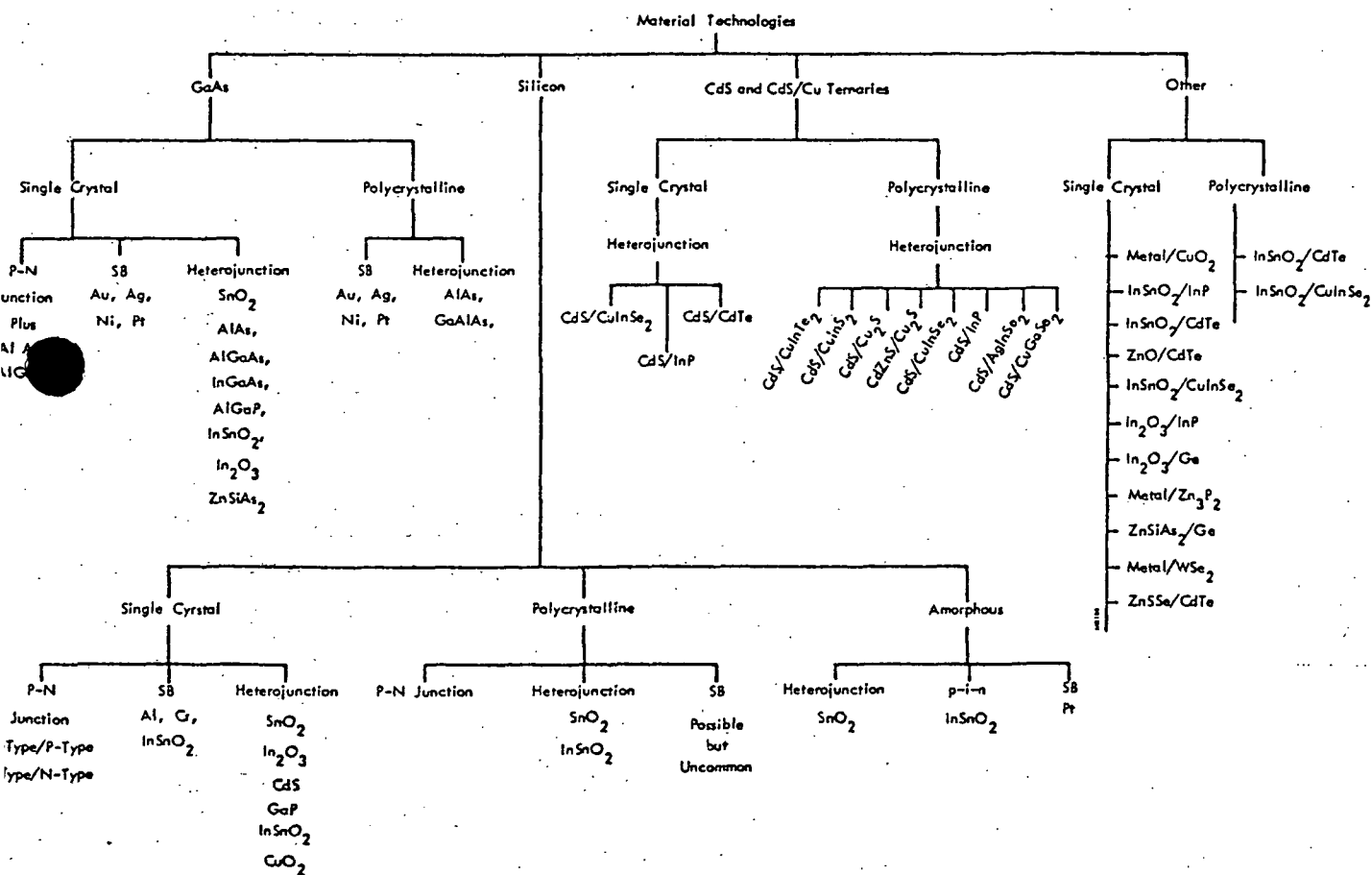


Source: JPL

## TECHNOLOGY OPTIONS

To add perspective to the number of photovoltaic technology options available, the principal material/crystalline structure options are shown in Figure 3.8. Included are basic material type, crystal orientation cell structure, and materials used to form the junction with the basic materials. While this is not an all-inclusive list, it does demonstrate the large number of possible photovoltaic technology bases that can be pursued.

FIGURE 3.8  
PHOTOVOLTAIC TECHNOLOGY OPTIONS



### 3.2 POLYCRYSTALLINE SILICON

#### TECHNOLOGY DESCRIPTION

Thin films of polycrystalline silicon offer significant cost reduction potentials in the production of photovoltaic cells over that of single-crystal silicon wafer devices. The potential cost reductions are associated with reduced material usage and waste (i.e., kerf losses in slicing), reduced energy for fabrication, and adaptability to continuous-flow processing. While significant progress has been made in the last five years, viability on an economic/performance basis still eludes this technology area in the field of photovoltaics.

More companies than ever are now investigating various aspects of polycrystalline silicon cells. The level of effort as measured in dollars and the number of full-time personnel, however, is still well below that of the single-crystal silicon programs. This should not be looked upon negatively, but rather as a realization of the prioritizing and proportioning of finite resources to those areas (i.e., single-crystal silicon) that offer the more likely probability of technical and commercial success. As technical progress and feasibility are demonstrated in the laboratory, ever-increasing resources will be devoted to developing this technology into a viable commercial venture.

#### SILICON SUPPLIED FROM SLICED INGOTS AND THIN-FILM DEPOSITION

The fabrication of polycrystalline silicon solar cells has been based upon obtaining the silicon from either wafer slices of polycrystalline silicon ingots (similar to single-crystal approach) or the deposition of silicon in thin-film polycrystalline form on substrate materials. The ingot approach has provided the best cell performance characteristics due to the large grain sizes (greater than 100  $\mu\text{m}$ ) of the silicon, but has all of the high costs and wastes associated with the single-crystal silicon approach. The use of this approach, however, has permitted studies of the effect of grain size and grain boundaries (through the variation in grain size) on cell performance characteristics. The ingot approach could conceivably offer cost/performance trade-off advantages to single-crystal silicon but would fall far short of the potential for the thin-film approach.

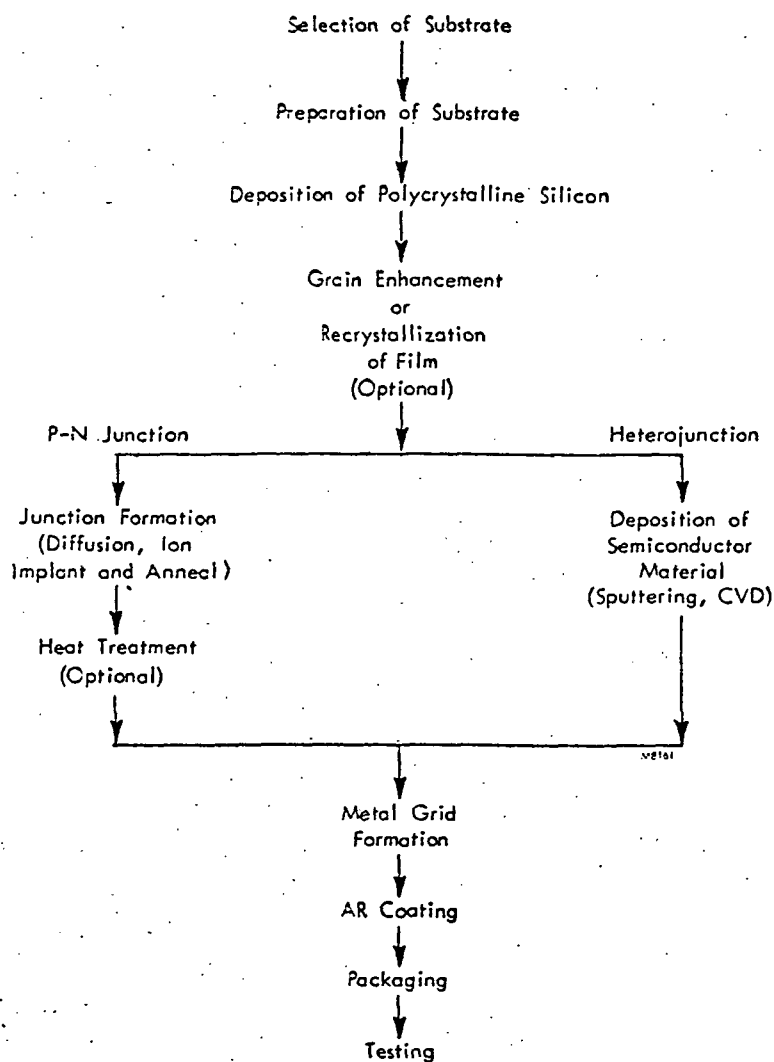
For purposes of this report, the thin-film approach will be discussed as the principal polycrystalline silicon technology base. Reference will be made to ingot-based cells for comparative purposes only.

## MANUFACTURING FLOW BEGINS WITH SUBSTRATE SELECTION

A generalized flow chart for the formation of polycrystalline silicon solar cells is shown in Figure 3.9. The selection of the substrate material should meet the following characteristics:

- Low cost
- Chemically inert
- Readily available
- Compatible thermal coefficient of expansion

FIGURE 3.9  
GENERALIZED MANUFACTURING FLOW CHART FOR  
POLYCRYSTALLINE SILICON SOLAR CELLS



The various materials that have been tried include titanium, molybdenum, graphite, sapphire, aluminum oxide, ceramic, and fused silica. Each of these materials have one or more outstanding characteristics, but few, if any, represent a good compromise of all the needed characteristics. At present, graphite and ceramic appear to be the best choices, but this area is far from final determination.

In general, the preparation of the substrate is nothing more than a cleaning and degreasing operation. Depending upon the chosen material, there may, however, have to be an interface material deposited on the substrate to enhance the subsequent growth of the polycrystalline silicon layer and/or act as electrical contact for one side of the cell structure.

#### MANY OPTIONS FOR SILICON DEPOSITION

The deposition of the silicon layer is accomplished through one of several methods, including:

- Chemical vapor deposition (CVD)
- Vacuum deposition
- Dip or wipe process
- Energy beam deposition
- Sputtering
- Plasma-assisted evaporation

Chemical vapor deposition is the controlled reaction of gases in an enclosed chamber wherein silicon is deposited on the heated substrate. Appropriate dopants can also be introduced into this process.

Vacuum deposition is the bombardment of polysilicon in a crucible by an electron beam in a vacuum chamber. The electron beam imparts energy to the polysilicon, causing it to evaporate and deposit on the heated substrate. The use of dopants in these systems is possible but is very difficult to control and is generally not used.

In the dip or wipe process, the properly prepared substrate is dipped into a doped silicon melt and slowly removed. The silicon grows or forms on the substrate in long, narrow grains. The substrate may be wiped across the surface of the melt also. This wipe approach has been referred to as "ribbon against drop" pulling process in the literature.

The energy beam deposition process is based upon the decomposition of silicon bearing gases such as  $\text{SiCl}_4$  or  $\text{SiHCl}_3$  when introduced into an rf field. The resulting plasma stream generated is directed at suitable heated substrate material by way of a nozzle. Polycrystalline layers of silicon are grown on the substrates. Dopants can easily be introduced and controlled in this system.

The plasma-assisted evaporation process is a combination of the vacuum deposition process and an rf field to direct the silicon ions toward the substrate material. This makes the vacuum deposition process more efficient in material usage.



## SILICON INGOTS OBTAINED BY PULLING OR CAST PROCESS

The ingots are formed by either a pulling process (same as in the single-crystal method), followed by a float-zone grain enhancement step or by the casting method.

The basis of the cast method for generating polycrystalline silicon is the controlled solidification of a silicon melt. In effect, a seed of single-crystal silicon is placed in a melt of polysilicon. The seed is maintained at a controlled temperature below that of molten silicon. The temperature of the melt near the seed is slowly reduced. This allows nucleation of crystal growth areas to form on the surface of the seed. These crystals continue to grow as the temperature of the melt is reduced in a radial direction from the seed.

Under proper conditions, single-crystal material can even be produced in this fashion up to 4-inch-diameter ingots. These single-crystal ingots are of limited length, however, and reproducibility is not characteristic of the process.

Other cast methods also depend upon controlled solidification of a silicon melt but differ in that a substrate material properly prepared enhances nucleation of crystals when the melt is cooled. Still other methods depend strictly upon the controlled cooling of a silicon melt with the result being a random crystalline formation.

The real intent of these processes is to produce large-grained polycrystalline silicon ingots, sheets, or slabs that can ultimately be sliced or segmented into suitable wafer form. The reproducibility in some of these processes is very good, as testified by commercial availability of such material.

## REFINEMENT OF GRAINS POSSIBLE

The grain enhancement or recrystallization of the film is an optional process step. Its principal purpose is to increase grain sizes by localized melting and recrystallization of the silicon layer, or to properly prepare the grain boundaries to act as part of the junction.

The recrystallization processes include:

- Ribbon-to-ribbon (RTR) process
- Pulsed beam process

The RTR process uses a laser beam to melt the silicon layer in localized areas by a scanning procedure. The recrystallization results in larger grain sizes. The pulsed-beam process is a two-step procedure. The first pulse of energy is spread over a large area, causing a shallow melt and a regrowth of crystals having grain boundaries perpendicular to the surface. The second pulse is localized to a narrow band and is laterally scanned across the material. This second pulse of energy has a similar effect to the RTR laser beam in that the recrystallization silicon is composed of much larger grain sizes.

The grain enhancement process relies upon the use of a short, lightly doped diffusion step. During the diffusion, the dopants diffuse part-way down the grain boundaries. The top portion of the polycrystalline silicon is then etched off. The structure is then ready for a normal diffusion process to form the junction. The dopants previously diffused into the grain boundaries act as an extension of the junction area down the grain boundaries. This process can only be used on structures having grain boundaries perpendicular to the surface.

#### CELL STRUCTURE BASED ON P-N JUNCTION OR HETEROJUNCTION

The formation of polycrystalline silicon solar cell junctions has to date taken the form of either a P-N junction or a heterojunction. Some Schottky-barrier devices have been reported, but they are in the minority. The P-N junction structure is generally formed by a diffusion process. If the polycrystalline layer was not previously doped during the silicon deposition process, then a double diffusion is required to form the P-N junction.

An alternative method to diffusion is the ion implant approach. Here the surface is bombarded by ions of the proper dopant and is then followed by an annealing process. The anneal may be either a heat treatment or a variation of the pulsed beam process.

For further enhancement of the P-N junction's cell characteristics, a heat treatment in hydrogen or other atmosphere is used on occasion. Such heat treatments are common within the semiconductor industry to enhance junction characteristics.

The heterojunction structures are formed by the interface of two semiconductor materials, one of which in this case is silicon. One of the most commonly used interface materials is tin oxide ( $\text{SnO}_2$ ). Another is indium tin oxide. These layers are usually deposited by either sputtering or CVD techniques.

Historically the heterojunctions have been reported as having the better cell performance characteristics. This has been due to the use of polycrystalline silicon from sliced ingots having large grain sizes (greater than  $100\text{ }\mu\text{m}$ ).

The remaining steps of the process for either P-N junction or heterojunction structures includes metal grid formation, application of anti-reflective (AR) coatings, packaging, and testing. There is a long list of variations to the generalized flow of manufacturing steps that have been described in this section. The intent has been to broadly categorize the variations to include all of the major reported approaches.

## GOVERNMENT SUPPORT EXISTS IN ALL PROCESS AREAS

Virtually all of the process steps described above have been reported upon through some related government contract. The development of the polycrystalline silicon technology base is well supported by a host of government research and development contracts. This is especially true for the thin-film P-N junction approach.

## TECHNOLOGY PERFORMANCE CHARACTERISTICS

A summary of the performance characteristics of polycrystalline silicon photovoltaic cells is shown in Table 3.1. The large variability in the parameters is generally related to the variability in grain size of the material used. The higher end of the parametric spread is all associated with 30  $\mu\text{m}$  or larger grain size material. The low end of the distribution is represented by a mixture of grain sizes ranging from a few microns to 33  $\mu\text{m}$ . This indicates influences other than grain size are also retarding cell performance.

TABLE 3.1  
PERFORMANCE CHARACTERISTICS OF THIN-FILM POLYCRYSTALLINE SILICON  
PHOTOVOLTAIC CELLS

Parameter	$V_{OC}$ (Volts)	$J_{SC}$ ( $\text{mA}/\text{cm}^2$ )	FF	$\eta$ (Percent)	Cell Area ( $\text{cm}^2$ )
Maximum Reported	0.56	28	0.71	10.1	20
Range	0.2-0.56	5-28	0.4-0.71	3-10.1	1-20
Typical	<0.5	<10	0.55	5	2

The principal elements identified, other than grain size, that negatively influence cell characteristics include contact resistance, series resistance of bulk material, impurities, grain boundary carrier traps, and low carrier lifetime. Growth and deposition conditions of the various material layers are also identified as having significant influences on results.

The calculations of theoretical limits of the performance parameters is hindered by a lack of adequate understanding of grain boundaries and related influences. The intermediate goal of the thin-film polycrystalline silicon laboratory programs is to demonstrate 10 percent efficiency levels on cell sizes of at least

1 cm<sup>2</sup>. While no upper limits have been firmly established, it is believed that efficiencies of 10 to 14 percent are possible. Key to this will be the development of a thin-film silicon deposition process that produces large grain sizes of at least 15 to 20  $\mu$ m, and preferably larger.

To meet the low cost of manufacturing expectations of this technology base, a suitable substrate material will also need to be identified. Not only will it need low cost characteristics, but it must also withstand the thermal shocks of the resultant deposition processes. Thermal compatibility in its coefficient of expansion and its capability to remain inert at elevated temperatures will be critical parameters that will influence cell performance characteristics.

Instability has not typically characterized thin-film silicon cells. Sufficient quantities of cells and adequate testing of them has not, however, been done to verify this issue. Much insight into the likelihood of instability should be able to be drawn from the single-crystal silicon work that is far more advanced. The thin-film silicon problem is compounded, however, by the presence of grain boundaries and the possibility of ion migration along these boundaries.

Entrapment of impurities from either the original silicon source or from autodoping effects of the substrate material may be more pronounced in polycrystalline materials than in single-crystal approaches. The detection of such impurities and their ultimate effect may also be complicated by the presence of the grain boundaries.

## COMMENTARY ON COLLATERAL TECHNOLOGY REQUIREMENTS

### ELECTRICAL CONNECTIONS

In the selection of a proper thin-film polycrystalline structure, the method and effectiveness of the electrical connections becomes a critical item. Electrical connection at the cell/substrate interface is usually accomplished through the use of an interface material deposited on the substrate prior to deposition of the silicon layer. That deposited layer must have a set of unique characteristics. First, it must adhere to the selected substrate material. Second, it must be electrically conductive. Finally, it must allow nucleation and growth of silicon. The compatibility of the last two characteristics generally eliminates most materials. Some form of silicon (i.e., silicon carbide, metallurgical silicon, silicon wafer) has normally been used. None of the present solutions are totally satisfactory due to either technical or cost considerations.

An alternative method is to form a "mesa" structure, where a portion of the deposited polycrystalline silicon layer is left exposed. It then becomes available for electrical contact once it has been metallized.

Neither of these approaches have proven acceptable to date due to contact and series resistance problems. This still remains a problem area and must ultimately be resolved.

Contact to the cell on the nonsubstrate side is done through conventional metal-grid formation methods (i.e., evaporation/etch, evaporation through grid mask, screen printing, pressure contact of metal grid or screen, etc.). The problem is compounded, however, when trying to contact fine grain structures. The lateral series resistance is increased many times by the presence of grain boundaries, causing current collection to be severely limited.

In addition, the grain boundaries can also act as reflectors of carriers. If a grain is not directly contacted by the metal grid, the carriers may never be collected from that localized area. This then severely limits current power output and efficiency. Thus there is a need for large grain sizes, at least in one lateral direction, and an optimized metal grid structure to enhance collection of carriers.

Once such an arrangement is devised, then methods for ensuring excellent ohmic contact must also be developed. Accomplishing good ohmic contact to the grain surface without causing shorts or low resistant shunt paths through the grain boundaries to the substrate will be difficult to accomplish. Even if accomplished, there must be consideration of the possibility of metal ion migration with time through the grain boundary areas.

## DEVICE AND PACKAGE INTERACTION

The ultimate benefits of polycrystalline thin-film silicon can be maximized only if large-area sheets of some selected cell structure can be manufactured. The sheets may be in the form of a few large cells or an interconnected pattern of many small cells. Whatever the final format, the manufacturing economies dictate a functional integration of cell structures, their electrical interconnection, and semi-final packaging materials.

Development of such functional integrated packaging systems cannot yet be pushed, since final cell structures and deposition methods have not been resolved. This area will require significant attention and resources in time if polycrystalline thin-film silicon is to be a viable economic option in the future.

## ENVIRONMENTAL IMPACTS ON CELL RELIABILITY

The development of cells based on this thin-film technology is not sufficiently advanced to provide any quantitative data on the impact of environmental influences on cell stability or long-term reliability. Implications can be drawn from field tests associated with single-crystal cells and those made from large-grain polycrystalline material. Since moisture can have a degrading effect upon metal grid and interconnect systems in these structures, it will undoubtedly have a similar effect upon polycrystalline structures. Appropriate packaging precautions will thus be required to eliminate moisture penetration.

No inherent self-destruct mechanisms have been identified with single-crystal silicon, and none are expected to be associated with polycrystalline silicon. The influence of the presence of a grain boundary in the polycrystalline structure adds a new dimension to the reliability question, however. Thermal shocks may cause cracking or other detrimental effects not seen in single-crystal structures. They may also act as concentration centers for ionic impurities from within or outside the cell. The verification and ultimate influence of this has yet to be established.

There is no conclusive evidence yet to suspect that polycrystalline cells will be less reliable in terrestrial environments than single-crystal cells. It is conceivable, however, that packaging requirements will be tougher to meet with polycrystalline cells due to grain boundary effects.

## ENVIRONMENTAL IMPACT OF MANUFACTURING PROCESS

The greatest environmental impact is expected to be at the silicon mining and refining locations. Here the control of silicon dust is the principal concern. Inhalation of silicon dust can result in the generation of fibrotic tissue in the lungs, leading to the condition known as silicosis.

The production of metallurgical silicon is through the reduction of quartz in an electric arc oven using coke as the carbon source for the arc. The emissions from such an operation include carbon monoxide, which ultimately becomes diluted CO<sub>2</sub>, and submicron-sized silicon particulates. The silicon particulates are not toxic but do add to the overall level of irritating respirable particulates in the atmosphere.

Those processes associated directly with the cell manufacturing steps are not uniquely different from those already existing in the semiconductor industry. Negative impacts on the environment are not expected, even with a significant expansion in volume production.

In the cell production area, the emissions of toxic fumes from dopants is the major problem area. Boron and phosphorous can be toxic in some gaseous forms. They can cause anemia, nervous disorders, and gastrointestinal damage. An extension of present semiconductor control method should be sufficient to provide worker and environmental protection in this area.

#### IMPACT OF PRESENT GOVERNMENT PROGRAMS

Only recently has there been an expansion of government programs to investigate basic mechanisms in polycrystalline materials. Previously this technology base was not pursued with great vigor. This is understandable, as single-crystal structures offered greater short-term benefits, both technically and commercially.

A number of government-supported programs are now established to investigate deposition methods, effects on grain boundaries and their characterization, theoretical models, various cell structure concepts, and characterization of suitable materials for both substrates and cell formation. Because they have only recently been established, the programs are not expected to produce results in the very near future. However, the impact of these and future programs should provide a significant increase in the development pace of polycrystalline silicon cell knowledge and cell performance characteristics.

#### STATE OF DEVICE TECHNOLOGY

##### MATURITY LEVEL

The polycrystalline thin-film technology base is still confined to the laboratory environment. Many fundamental questions are yet to be sufficiently answered to justify any commitments to pilot production facilities. Proving feasibility is still dominant over any attempts to optimize or judiciously select among the many possible cell structure concepts.

Many companies are now devoting resources (although limited in many cases) to this technology base, primarily through government support contracts. The dominant companies in producing functional cells in the laboratory include Honeywell, Exxon, Motorola, and Solarex. Several academic institutions have also demonstrated cells. They include Johns Hopkins University, SMU, Colorado State University, and State University of New York.

Companies producing large-grain polycrystalline silicon ingots or wafers include Wacker, Solarex, and Crystal Systems. Grain enhancement methods are being studied by IBM, SMU, Motorola, and Spire Corporation. The effects of grain boundaries are being pursued, with the support of government contracts, at Motorola, Westinghouse, and Hughes. Theoretical models are being developed, again by way of government contracts, at Solarex, Westinghouse, RCA, and several universities. Extensive examination of substrate materials, not only for polycrystalline silicon cells but for other technologies as well, is being performed by Rockwell.

As a result of the above-mentioned areas of activity, the accumulation of knowledge in this technology base is expected to quicken compared to previous years. Even with this increase in activity, the technology is not expected to move out of the laboratory environment for several more years.

#### REPRODUCIBILITY AND CELL SIZES

Reproducibility has not been possible with most of the fine-grained structures. The larger-grained cells have, however, shown greater reproducibility, although not so universally. This indicates several unidentified mechanisms are present that have an effect upon cell performance characteristics. These influences are most likely associated with substrate autodoping, layer growth conditions, impurity levels, contact resistance, and grain boundary effects. Most of these suspect areas have not been sufficiently characterized to quantitatively determine their impact.

Present-day cell sizes are relatively small, typically 2 cm<sup>2</sup> or less. Cell sizes are limited by the ability to control deposition characteristics over a large area. No scale-up in deposition equipment has been attempted, and will not likely occur until reproducibility of acceptable cell structures has been demonstrated. At the present time, the best deposition process has not yet been defined and until this is forthcoming, it would not be wise to even consider equipment scale-up efforts.



## SUMMARY OF MAJOR BARRIERS TO COMMERCIALIZATION

### TECHNICAL BARRIERS

The following major technical barriers must be resolved before any optimization or scale-up of selected cell structures can be anticipated:

- Lack of understanding of grain boundary effects
  - Limitation on efficiency.
  - Characterization of growth conditions for large-grain-sized material.
  - Influence of substrate material on grain size
- Unknown effects of impurities from substrate and silicon materials
- Selection of adequate substrate material
- Selection of cell structure and associated materials such as dopants for P-N junctions and appropriate interface material for heterojunctions
- Lack of understanding of limitations on carrier lifetimes

### MANUFACTURING BARRIERS

Once technical feasibility has been demonstrated, certain manufacturing limitations must be overcome. They include:

- Selection and optimization of large-scale deposition process equipment
- Optimization of cell structure
- Functional integration of cell structure and packaging materials
- Establishment of proper process, quality, and environmental controls

## OTHER RELATED INFLUENCES TO COMMERCIALIZATION

There are other influences that could affect the development pace of this technology base in either positive or negative fashion. These areas of influence include:

- Determination of long-term field reliability
- Nature of continued government support contracts
- Development pace of amorphous silicon and other thin-film technologies
- Level of resources devoted to research and development activities in this technical area

### 3.3 AMORPHOUS SILICON

#### TECHNOLOGY DESCRIPTION

There are three advantages to producing photovoltaic structures from amorphous ( $\alpha$ ) silicon:

- Since the properties of  $\alpha$ -silicon are independent of the substrate on which it is grown, then extremely inexpensive substrate material can be used.
- The silicon content of such cells is extremely low.
- Process steps are few and relatively simple.

While not yet proven, it is felt that cell efficiencies can be raised to over 15 percent. The process steps at present also appear to be adaptable to continuous-flow manufacturing procedures.

#### MANUFACTURING FLOW DIFFERS GREATLY FOR EACH CELL STRUCTURE TYPE

The basic process for  $\alpha$ -silicon structures is based on the decomposition of silane ( $\text{SiH}_4$ ) onto a substrate material. A set of generalized manufacturing flow charts for the most common cell structures is shown in Figure 3.10. The three most common structures involved are:

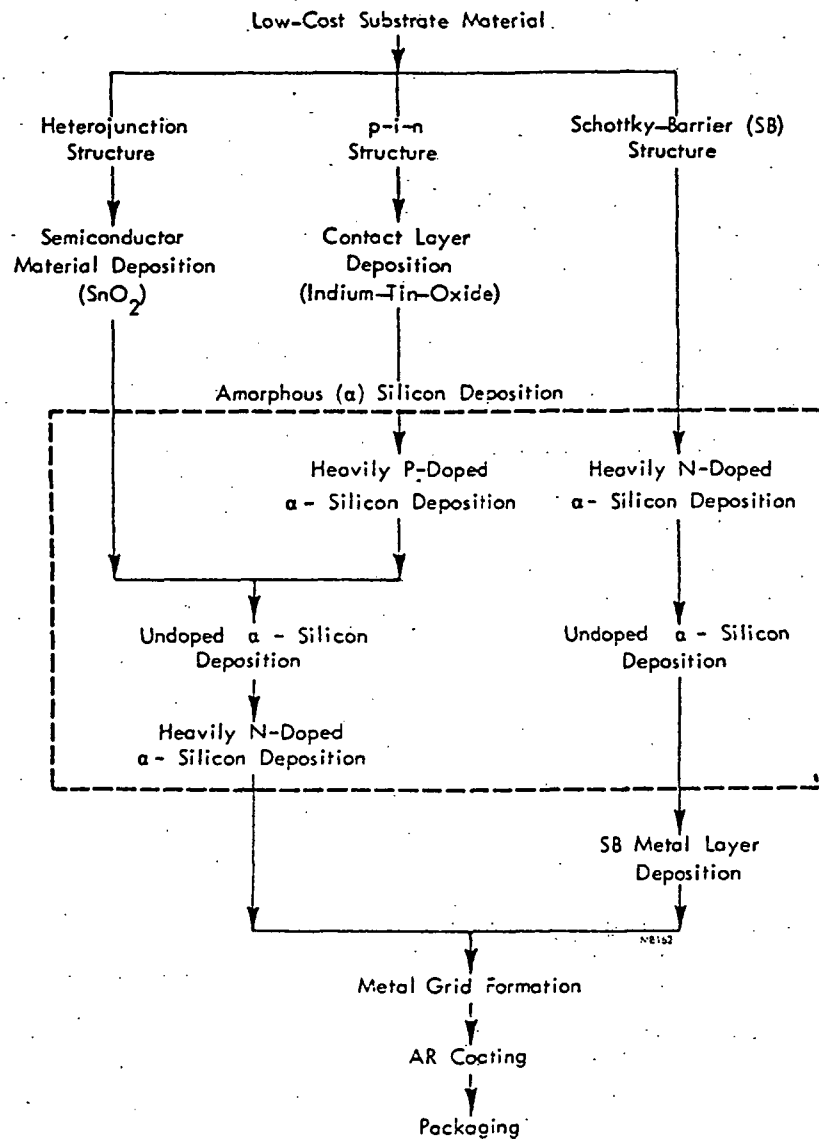
- Heterojunction--Junction formed at interface of two different semiconductor materials, one of which is  $\alpha$ -silicon
- P-i-n structure--Structure composed of a sandwich of heavily P-doped  $\alpha$ -silicon, intrinsic  $\alpha$ -silicon, and heavily N-doped  $\alpha$ -silicon
- Schottky barrier (SB)--The junction is formed at the interface of a metal layer and  $\alpha$ -silicon

The most commonly used substrate material is glass, although several other materials, such as thin sheets of steel and other metals, molybdenum, and graphite, have also been tried. Unlike polycrystalline structures, amorphous silicon does not depend upon substrate conditions for minute growth sites. The  $\alpha$ -silicon essentially condenses onto the substrate rather than growing in an orderly manner from nucleation sites.

#### THREE BASIC OPTIONS FOR $\alpha$ -SILICON DEPOSITION

The semiconductor material deposition in the case of heterojunctions and the contact layer deposition for the p-i-n structures use standard vacuum evaporation processes. This also applies to the barrier metal layer for SB structures. The unique part of the process for each of the structures is the amorphous silicon deposition process.

FIGURE 3.10  
MANUFACTURING FLOW CHART FOR AMORPHOUS SILICON  
PHOTOVOLTAIC SOLAR CELLS



There are three methods for deposition of  $\alpha$ -silicon materials. They are:

- rf induction coupling
- Capacitance coupling
- Sputtering

Other methods have been postulated, but these three have been the methods by which functional cells have been produced to date.

The rf induction coupling method of deposition produces a cold flame glow-discharge atmosphere when silane ( $\text{SiH}_4$ ) is introduced into the rf field. In this environment, the silane decomposes and the silicon condenses out onto any hot surface within the rf field. By raising the substrate material temperature to the  $300^\circ\text{C}$ - $400^\circ\text{C}$  range, the silicon will condense onto the substrate in an amorphous crystalline orientation. This is an efficient method of deposition, as virtually all the silicon condenses onto the hot substrate, rather than the walls of the deposition chamber, which are kept relatively cool.

The capacitance coupled process is essentially the same, except the rf field is replaced by an electric field produced by a parallel plate capacitor. The silane decomposes between the plates of the capacitor, due to the electric field produced from the application of dc or ac voltages across the capacitor. Placing the substrate material on one capacitor plate and heating it to temperatures in the  $300^\circ\text{C}$  to  $400^\circ\text{C}$  range will produce the proper conditions for the silicon from the decomposed silane to condense onto the substrate.

Standard sputtering procedures can also be used to deposit amorphous silicon layers. This technology has not until just recently been used for  $\alpha$ -silicon solar cells. Sputtering is a reasonably developed process and may offer the shortest route to a large-scale continuous-flow process. The efficiency of deposition may, however, not be as good as in the case of the rf and capacitance coupled methods.

Doping of the  $\alpha$ -silicon layers in the rf and capacitance coupled processes is accomplished by introducing the dopant in gaseous form, such as phosphine, at the proper time in the deposition cycle. By having no dopant present, intrinsic amorphous silicon is deposited.

#### SILANE IS THE CRITICAL INGREDIENT

The essential ingredient used in  $\alpha$ -silicon processes is silane ( $\text{SiH}_4$ ). Silane is a by-product of the refinement of ferro- or metallurgical-grade silicon. Other by-products produced include silicon tetrachloride ( $\text{SiCl}_4$ ), trichlorosilane ( $\text{SiHCl}_3$ ), dichlorosilane ( $\text{SiH}_2\text{Cl}_2$ ), and recyclable polymers. The trichlorosilane, when exposed to heat, hydrogen, vacuum, and an electric field, is used for the production of polysilicon for the single-crystal silicon solar cell technology base.

Silane is one of the more expensive ingredients in the  $\alpha$ -silicon process. An alternative production process has been developed by Union Carbide as a result of the JPL program designed to reduce the cost of polysilicon. The silane production is an intermediate step in the overall Union Carbide process. Silicon is ultimately produced by pyrolysis of the silane. Several pyrolysis methods are under study, but no firm selection has yet been made.

The silane production portion of the process is well established and documented, however. It could very easily be used to produce inexpensive silane required for the  $\alpha$ -silicon processes. Scaling up of the process, however, must be analyzed closely to determine the true economics. This undoubtedly will be part of the present JPL polysilicon cost-reduction program.

STRUCTURES RELATIVELY SIMPLE Cross-sectional views of the three basic structures of  $\alpha$ -silicon cells are shown in Figure 3.11. Cell efficiencies have been the highest on the SB structures but have also shown the greatest degradation. Total thicknesses of these structures, not including substrate material, is less than 5  $\mu\text{m}$ . By comparison to other technologies, these structures are relatively simple.

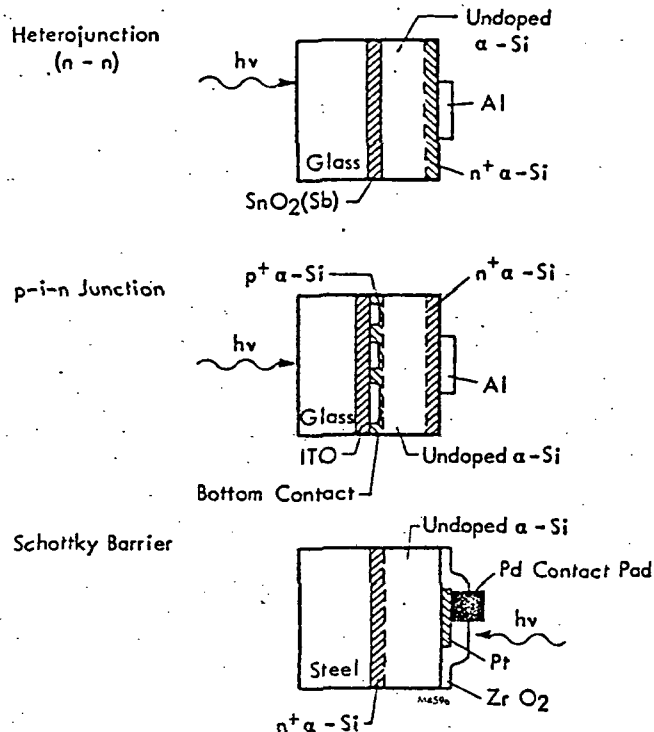
#### TECHNOLOGY PERFORMANCE CHARACTERISTICS

Only a limited number of  $\alpha$ -silicon cells have been generated to date. Thus little data has been forthcoming in this technology field. The open-circuit voltages ( $V_{OC}$ ) have under best results been reported near 0.85 volts. This is the highest  $V_{OC}$  of the advanced thin-film solar cell technologies. The typical values are somewhat lower, being in the 0.7 to 0.8 volt range. Contact resistance of the metal-grid system heavily influences this parameter. There is also some indication of a sensitivity of  $V_{OC}$  to dopants and conditions of deposition.

The short-circuit current density ( $J_{SC}$ ) ranges from 10 to 15  $\text{mA}/\text{cm}^2$  and has been one of the limiting parameters of  $\alpha$ -silicon structures. It appears to be very sensitive to dopants and deposition conditions also.

The fill factors (FF) are typically 0.5 or less, but samples have been produced with values between 0.60 and 0.65. The sensitivity of FF to deposition conditions, concentration levels, internally-generated junction electric fields, and other parameters is not fully understood.

FIGURE 3.11  
CROSS-SECTIONAL VIEW OF THE VARIOUS AMORPHOUS  
SILICON SOLAR CELL STRUCTURES



Cell conversion efficiency ( $\eta$ ) ranges from 1.5 to 6 percent. The higher the efficiency, the less stable the cells have been. In addition, the larger the area of the cell (which has ranged from  $1 \text{ mm}^2$  to  $3 \text{ cm}^2$ ), the less stable the efficiency. Typical efficiencies are in the 2 to 3 percent range. Efficiency appears to be influenced by the hydrogen content and the number of defects (traps) within the  $\alpha$ -silicon portion of the structure. These are closely tied to deposition conditions. Even with these results, industry sources are confident efficiencies in excess of 15 percent are ultimately possible.

Instability has generally characterized most amorphous silicon cells to date. They are sensitive to OH ions, and the resulting degradation is not reversible. Little else is known about the inherent failure modes of  $\alpha$ -silicon cells. Very few have actually been packaged in final form, and none have been field tested. No known self-destruct mechanisms have been documented to date.

## COMMENTARY ON COLLATERAL TECHNOLOGY REQUIREMENTS

### DEVICE AND PACKAGE INTERACTION

To take full advantage of the intrinsic characteristics of thin-film devices, and in particular  $\alpha$ -silicon, the concepts of discrete devices must be replaced by the production of large sheets of solar cells functionally integrated with their final packaging material, or at least semi-final packaging material. Only through such a concept can extremely low-cost modules or arrays be fabricated.

Development of such a system differs significantly from any programs presently being directed by JPL. While elements of the Low-Cost Solar Array Program may be applicable, it is most probable that a unique and specifically-focused program will be needed to fully develop the  $\alpha$ -silicon large-area products.

### DEVELOPMENT OF MANUFACTURING EQUIPMENT

Once the basic process and structure has been reasonably solidified, there will exist a need for the development for continuous-flow deposition equipment. The nature of such equipment will probably resemble the large thin-layer coating equipment used in the photographic film and copying industries. The equipment will have the characteristics of automatic operation, low maintenance, and continuous flow. Panel sizes will need to be typically 4 feet ( $\approx 125$  cm) wide or multiples thereof.

Defect-density control will be a major problem area in designing large-scale production equipment. Depending on structure design and the sensitivity to deposition conditions, the defect density level, even if no worse than present-day levels for photographic film, may be too high for economic viability.

### ENVIRONMENTAL IMPACTS ON CELL RELIABILITY

The long-term field reliability of  $\alpha$ -silicon cells is virtually unknown. Industry sources feel that latent failure modes are unlikely, but only through extensive field testing can it be assured.



A sensitivity to OH ions has been identified as having a degrading and nonreversible effect upon cell performance. Since OH ions are readily available in the environment, the necessary packaging precautions will be required. In effect, this means moisture-resistant packaging of cell structures is required as a minimum, and possibly even an oxygen barrier layer may be needed.

## ENVIRONMENTAL IMPACT OF MANUFACTURING PROCESS

The principal steps associated with thin-film  $\alpha$ -silicon production are:

- Mining of silicon ore
- Production of metallurgical-grade silicon
- Production of silane
- Production of  $\alpha$ -silicon

No significant environmental impact is expected from even a tenfold increase in silicon ore (quartz) mining operations. The control of silicon dust at the mining and refining locations is the principal concern. Inhalation of silicon dust can result in the generation of fibrotic tissue in the lungs, leading to the condition known as silicosis.

The production of metallurgical silicon is through the reduction of quartz in an electric arc oven using coke as the carbon source for the arc. The emissions from such an operation include carbon monoxide, which ultimately becomes diluted  $\text{CO}_2$ , and submicron-sized silicon particulates. The silicon particulates are not toxic but do add to the overall level of irritating respirable particulates in the atmosphere.

The waste products from the silane production are soluble metal salts; if disposed in ground deposits, they will rapidly be absorbed by the surrounding soil, groundwater, and surface waters. Disposal methods for such waste products have not been well developed. A potential problem area does exist if significant increased production results from photovoltaic requirements.

The reduction of silane to silicon results in relatively little in the way of pollutants that cannot be sufficiently controlled by passing the exhaust fumes through scrubbers.

## STATE OF DEVICE TECHNOLOGY

### MATURITY LEVEL

The amorphous silicon technology base is in an extremely early stage of development. Laboratory samples processed to various stages of competition for purposes of studying basic mechanisms characterize the bulk of cell production at this time. Optimizing the distribution of parameters is not as noteworthy as in demonstrating feasibility, even at minimal levels of performance.

The approach is primarily a controlled engineering one in which various conditions or parameters are systematically changed and results noted. This is the only viable approach available since the basic quantum theory and material science models have not been established. The lack of these basic understandings is one of the limiting barriers to the technology development pace.

There are presently no plans for immediate pilot-line production scale-ups. There are at various locations, however, plans for the scale-up of certain aspects of the process to allow generation of larger-area cells. This scale-up is primarily associated with the reduction of silane to amorphous silicon process. Through such scale-ups, the investigation of area-related problems (i.e., efficiency and stability) can better be performed. Present cell sizes are typically less than  $0.5 \text{ cm}^2$ . It is hoped with the scale-up of laboratory processes that between two and three orders of magnitude increases can be accomplished.

The principal industrial firm developing  $\alpha$ -silicon photovoltaic cells is RCA. Interest and resources are also directed at this technology base by Exxon, EIC Corporation, Battelle Columbus Laboratories, and several universities, including University of Delaware, University of Chicago, Duke University, and Paul Harvey University.

Reproducibility has not been established in any of the laboratory technologies. This is especially true for large-area ( $>1 \text{ cm}^2$ ) devices. Process parameters and the relationship of cell performance to such items as growth conditions has not been characterized to date. Primary emphasis has been upon varying process conditions to determine feasibility.

## SUMMARY OF MAJOR BARRIERS TO COMMERCIALIZATION

### TECHNOLOGY BARRIERS

The following technical barriers must be successfully addressed before a large-scale development program is warranted:

- Need to develop and understand models and the associated quantum theory of amorphous structures
- Determine which of the amorphous silicon deposition methods offer best large-scale, continuous-flow potential
- Characterization of basic mechanisms:
  - Deposition and growth conditions for amorphous silicon
  - Dopants and doping techniques
  - Carrier lifetimes
  - Ohmic contact
  - Effect of bulk  $\alpha$ -silicon series resistance
  - Effect of hydrogen during silicon growth
  - Sensitivity to OH ions and its implications
- Scale-up of laboratory equipment associated with silicon deposition to facilitate investigation of large-cell-area-related problems

### MANUFACTURING BARRIERS

Upon establishment of a solidified technology base, the following manufacturing barriers will need resolution

- Innovation in device structures; must depart from single-crystal analogies to produce functionally integrated devices and packages
- Develop source of inexpensive silane; possible solution is contained in Union Carbide's polysilicon plant design
- Scale-up of selected process and device structure will require development of low-maintenance equipment associated with:
  - Vacuum interlocks
  - Handling of large sheets (4' X 4' minimum)
  - Silicon deposition
  - Other material deposition

- Development of safety precautions as silane is pyrophoric
- Development of appropriate quality control procedures

#### OTHER RELATED INFLUENCES TO COMMERCIALIZATION

The following items could have an influence on the ultimate deployment of  $\alpha$ -silicon:

- Long-term reliability unknown; industry sources feel that latent failure modes are unlikely, but only through extensive field testing can it be assured
- Cost/performance characteristics of polycrystalline silicon and its development pace
- Confidence in long-term market development; without it there will be limited incentive to pursue research and development programs

### 3.4 SINGLE-CRYSTAL GALLIUM ARSENIDE

#### TECHNOLOGY DESCRIPTION

The pursuit of single-crystal gallium arsenide (GaAs) photovoltaic cells is driven by their inherent advantages over the single-crystal silicon-based cells. The GaAs response to the available terrestrial solar spectrum is far greater than for silicon. This is reflected in both higher theoretical and obtainable efficiency of conversion figures. In addition, GaAs structures can be made much thinner due to the fact that they absorb virtually all of their collectible energy within a few micrometers of depth. The final advantage of GaAs is that high-temperature operation is possible without substantial loss of efficiency. This makes single-crystal GaAs an excellent candidate for concentrator and hybrid system applications.

Along with these advantages, however, come some very restrictive characteristics. The areas of disadvantage include high material costs, less-developed equipment base, limited production capacity, and material-handling problems.

The basic building block of the structures is a doped single-crystal GaAs layer. Various layers of materials are then deposited or grown on top of this base layer to complete the final structure.

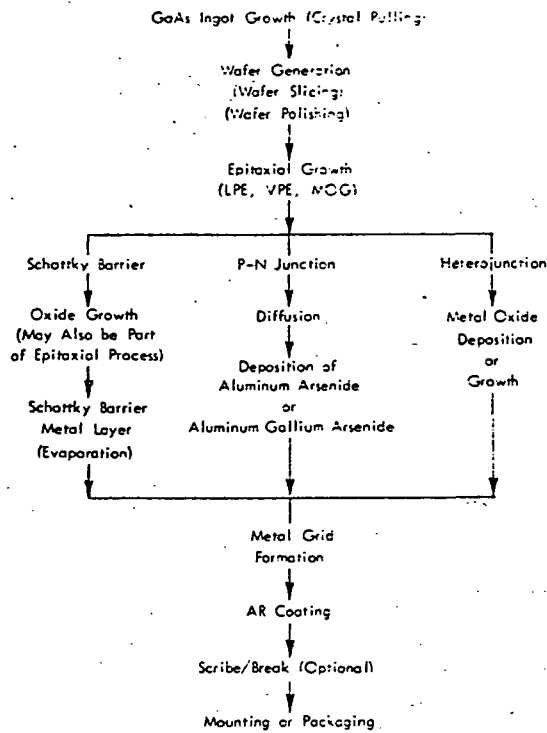
THREE BASIC STRUCTURES AVAILABLE                      Gallium arsenide photovoltaic cells typically take the form of a:

- P-N junction structure--The junction is formed by a diffusion of dopants into a doped epitaxial layer; may also include the deposition of another semiconductor layer
- Schottky barrier structure--The structure is a metal/oxide/GaAs sandwich
- Heterojunction structure--The junction is formed at the interface of two different semiconductor materials, one of which is GaAs

#### MANUFACTURING FLOW STILL EVOLVING

A generalized manufacturing flow chart showing the variations required for the formation of the above-mentioned structures is presented in Figure 3.12. Often specialized manufacturing flows incorporating unique process steps that differ significantly from that shown are used. This is more often associated with the Schottky barrier and heterojunction structures. A significant degree of experimenting is also occurring that will produce flows differing from that shown as the general case.

FIGURE 3.12  
GENERALIZED MANUFACTURING FLOW CHART  
FOR  
SINGLE-CRYSTAL GaAs PHOTOVOLTAIC CELL



#### GaAs INGOT GROWTH MORE COMPLEX THAN FOR SILICON

The GaAs ingot growth process is very similar to that of Czochralski-grown single-crystal silicon. Growth rates are significantly lower, however. The technology is not sufficiently developed to produce ingots in excess of 2 inches in diameter. More typical is one-half to one-inch-diameter ingots. This would be a limitation only if flat-plate systems were contemplated. Cells of this size are sufficient for concentrator systems. Complicating the ingot growth is the fact that the crystal-pulling operation requires high pressures, on the order of tens of atmospheres. This implies more complex equipment than in the silicon case.

Preparation of the sliced GaAs wafers is primarily a polishing operation. No significant problem areas have developed at this process step. Standard semiconductor wafer preparation techniques are used.

#### EPITAXIAL LAYER CRITICAL TO PERFORMANCE

Critical to the success of the single-crystal structure is the quality of the epitaxially grown GaAs layer on the substrate wafer. At present, there are three processes under investigation:

- Liquid-phase epitaxy--Layer is grown in the presence of liquid chemicals that must be controlled in temperature, flow rate, and mix

- Vapor-phase epitaxy--Layer is grown in the presence of chemical vapors containing gallium and arsenic that must be controlled in temperature, flow rate, and mix
- Metal organic growth (MOG)--Reaction of  $\text{Ga}(\text{CH}_3)_3$ , arsine ( $\text{AsH}_3$ ), and  $\text{H}_2$  in a moisture-free and temperature-controlled environment.

Each of these processes has its own inherent advantages and disadvantages from a cost and production control perspective. Various cell performance characteristics are also influenced in different fashions by each of these processes. This represents one of the most questionable areas of the single-crystal GaAs technology. There is a heavy need for a definitive answer to which process provides the best cost-performance trade-off.

#### FINAL STEPS OF MANUFACTURING FLOW BEING REFINED

The uniqueness of the process beyond the epitaxial layer is associated more with understanding characteristics of P-N and heterojunctions and the Schottky barrier structure. Reasonably well-documented process steps are used in the remainder of the process. The technical and engineering investigations that must be pursued at this point of the process are associated with reproducibility, quality control, reduction of material defect densities, and characterization of effect of dopants, manufacturing techniques, metal grid patterns, and cell mounting techniques.

#### EACH CELL STRUCTURE HAS ITS ADVANTAGE

Cross-sectional views of typical heterojunction, P-N junction, and Schottky barrier structures are shown in Figures 3.13, 3.14, and 3.15, respectively. The heterojunction structure has the potential advantage of improved collection efficiency of incident light over a broader wavelength spectrum compared to the P-N junction structure. The P-N junction, however, has been the most successful of all the GaAs-based structures due to its high practical conversion efficiency. The Schottky barrier approach offers the potential advantage of low temperature processes (compared to the P-N junction diffusions), adaptability to a polycrystalline thin film approach, and high radiation resistance.

FIGURE 3.13  
CROSS-SECTIONAL VIEW OF GaAs HETEROJUNCTION STRUCTURE

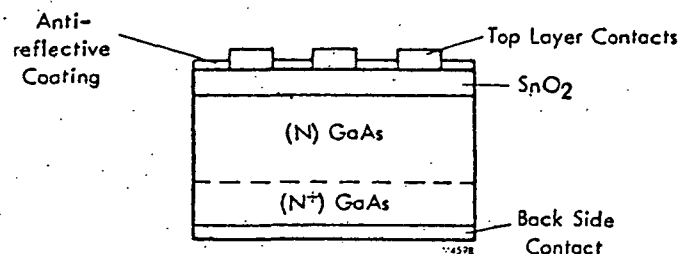


FIGURE 3.14  
CROSS-SECTIONAL VIEW OF GaAs P-N JUNCTION STRUCTURE

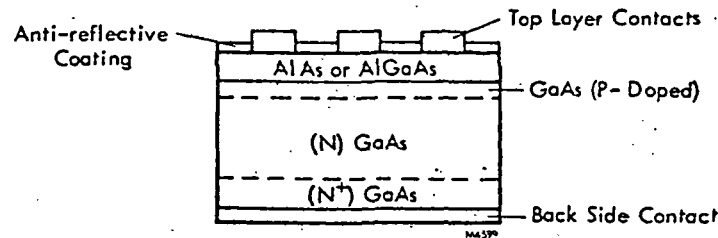
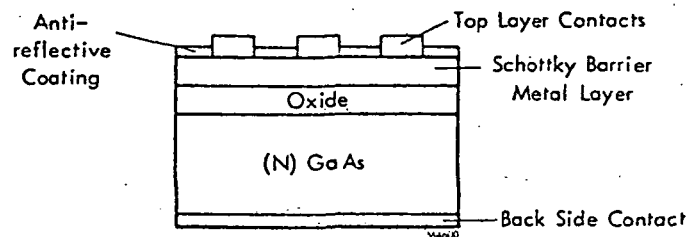


FIGURE 3.15  
CROSS-SECTIONAL VIEW OF GaAs SCHOTTKY-BARRIER  
SOLAR CELL STRUCTURE



### TECHNOLOGY PERFORMANCE CHARACTERISTICS

A summary of GaAs cell characteristics is shown in Table 3.2 for the P-N junction and heterojunction structures. The Schottky barrier structures have not yielded as good results. Efficiencies ( $\eta$ ) for such structures are seldom more than 10 percent, although IBM and JPL have reported values as high as 17 percent. The short-circuit current densities for SB structures are about 15 to 20 percent lower ( $19 \text{ mA/cm}^2$ ) than those shown in Table 3.2. The primary restriction on performance is due to low open circuit voltages of 0.55 to 0.60 volts and fill factors of no more than 0.6.

TABLE 3.2  
GENERAL CHARACTERISTICS OF GaAs SOLAR CELLS  
(P-N Junction and Heterojunction Structures)

Parameter	$V_{OC}$	$J_{SC}$	FF	$\eta$	Cell Size
Range	0.95-1.15 V	18-25 $\text{mA/cm}^2$	0.75-0.81	20%-25%	0.25-1.6 $\text{cm}^2$
Typical	1.1V	23 $\text{mA/cm}^2$	0.8	23%	0.5 $\text{cm}^2$



Cell sizes have remained relatively small. This has not been a severe limitation, however. The cells are generally destined for concentrator applications, and larger sizes would be of no great benefit.

Output power for these cells can range up to the 10-watt level (10 amps at 1 volt), with high concentration ratios. The efficiency at these high output power levels is heavily dependent upon the series resistance at the top contact region. Design of the top metal collection grid becomes critical, as well as ohmic contact characteristics.

Critical process parameters influencing cell efficiency have been identified as minority carrier diffusion lengths, contact resistance, layer thickness, and junction depths. Quantitative values for these parameters have in most cases been reasonably documented for various structures.

There are no indications of cell instability in the laboratory devices built to date. Variations in  $V_{OC}$  in Schottky barrier devices have been noted on occasion and traced to the oxidation process. This can be stabilized with proper growth and heat treatment procedures. The long-term stability of any of the cell structures has not been sufficiently verified in the field or laboratory.

## COMMENTARY ON COLLATERAL TECHNOLOGY REQUIREMENTS

### CELL MOUNTING AND HEAT REMOVAL

The primary use of single-crystal gallium arsenide photovoltaic cells is in concentrating systems. The concentration ratio in these systems can range to as high as 1,000. This produces extremely high cell temperatures and requires active cooling methods to maintain operating temperatures within reasonable limits (less than 200° C). Even with concentration ratios between 50 and 100, the cooling problems can be complex.

The removal of the transferred heat is generally accomplished via conduction through a solid heat sink or the use of recirculating liquids. The technologies involved are not mysterious but do require knowledge of thermodynamic principles and their implications if high efficient heat transfer is to be accomplished.

One of the most limiting features of the heat transfer mechanism is associated with the proper attachment of the solar cell to the heat transfer hardware. Problems in this area have also plagued the semiconductor industry for years in association with their high-power devices. The large discrete high-power rectifiers and power transistors are the devices having mounting problems that most typify those faced by the GaAs concentrator cell manufacturers. Such problems include:

- Proper selection of metal solders and flux
- Maintaining proper wetting conditions
- Temperature control during mounting process
- Surface cleanliness
- Elimination of voids

While potential problem areas and possible solutions can be extracted from the experiences within the semiconductor industry, the solar cell industry must develop different equipment and control methods due to larger area devices and the special hardware on which the devices must be mounted. To date, this has been done by hand, but large production facilities will require mechanized procedures.

#### COLLECTOR DESIGN

Significant programs are under the direction of Sandia for the development of concentrator hardware designs. The importance of this work cannot be downplayed. The balance of system (BOS) costs will have a significant influence on future market viability. Development of low-cost, high-concentration-ratio collector designs should emerge from the Sandia programs. The point to be made is that sufficient emphasis must be maintained on this aspect of the total system or advantages of improved cell performance, both technical and economic, will not be as beneficial.

#### ENVIRONMENTAL IMPACTS ON CELL RELIABILITY

The long-term reliability of the GaAs cells is thought to be excellent. This, however, has not been verified by field tests except in very limited cases. To date, most field failures have been associated with lens or mirror deterioration, open interconnect contacts, poor thermal contact of cells to hardware, and mechanical problems. The GaAs cells themselves have shown some signs of degradation, but not to a significant degree.

There exists a need for field tests or simulated laboratory tests to determine failure modes of the GaAs cells. Such tests should also indicate the proper encapsulation or packaging requirements for the cells. Present concentrator designs generally do not protect the cells from environmental conditions. Increased field testing may warrant a modification in this area.

## ENVIRONMENTAL IMPACT OF MANUFACTURING PROCESSES

Gallium is a by-product of aluminum and zinc refining. Aluminum ore reserves represent the major present gallium source in the US. The potential environmental impact of an increased demand for gallium is in the disposal of the waste sludge materials that result from processing aluminum ores to obtain the gallium. Gallium itself presents no significant environmental impact.

Arsenic is a by-product of commercial metal refining processes associated primarily with copper, gold, and silver ores. Major present US arsenic sources are contained principally within copper reserves. Initial increases in its demand could be satisfied from extraction of  $As_2O_3$  from the flue dust at the copper refineries. The subsequent As refining process represents no serious environmental problems as long as present OSHA standards are applied.

The production of the GaAs substrates requires equipment capable of extremely high pressures (i.e., 100 atmospheres) due to the high vapor pressure of arsenic. A leak within or an explosion of this equipment would result in significant quantities of arsenic into the air. The arsenic would oxidize to  $As_2O_3$ . This compound can cause skin irritation, fatigue, and liver and kidney failure, depending on the accumulated level of arsenic in the body.

The remaining cell process areas are not considered to be especially hazardous or potentially polluting. Application of present OSHA standards developed within the semiconductor industry should be sufficient to maintain these operations within safe limits.

For the high-concentration systems, the use of lenses will most probably dominate over reflective mirrors. These lenses are typically made of acrylics such as methyl methacrylate. While no significant pollution problems have been identified with these materials, a serious fire hazard does exist as these materials are flammable. Proper handling and processing procedures are well defined and should be made a part of any new facility installation.

## IMPACT OF PRESENT GOVERNMENT PROGRAMS

Virtually all organizations pursuing the development of single-crystal GaAs solar cells are or have been under contract to one of the major government agencies responsible for photovoltaic technology development. The principal agency has been Sandia, but programs have also been supported through SERI and JPL. In many cases, private company funds have also been applied toward GaAs technology advancement in addition to the government contract funds.

The impact of these contracts has been the stimulation of interest in developing a basic understanding of GaAs cells and their use in concentrating solar systems. The commercial firms most active in GaAs development already had a GaAs technology base established before receipt of a government photovoltaic contract. The benefit of the government contract was to focus and direct the technology toward photovoltaic applications. The major previous applications were in semiconductor light-emitting diodes, lasers, and fiber optic source and detector applications.

While great benefits have been derived from the issuing of government contracts, the method by which these contracts has been implemented has restricted greater industrial investments. Typical contracting practice establishes single-year contracts or limits the contractor to a single phase of a multiphase program. Industry is reluctant to provide matching funds or even more dollars than provided by the contract when no reasonable assurance of a second-year or second-phase contract is forthcoming.

To maximize industrial participation and increase leverage of government funds, multiyear and multiphase contracts need to be established. Disruption of work efforts and temporary abandonment of programs due to delays in negotiating follow-on contracts has brought severe economic hardship to small firms. As the larger firms approach the pilot line stage in GaAs technologies, longer-term contracts will be extremely vital to encourage investment of company funds.

This need for multiyear or multiphase contracts is more acute in the case of single-crystal GaAs than in most of the advanced technologies since this is the most developed technology base. Consideration for pilot production lines will be addressed in the near future.

## STATE OF DEVICE TECHNOLOGY

### MATURITY LEVEL

The state of maturity of GaAs device technology varies from a laboratory curiosity to apparent readiness for establishing a pilot line. With typical efficiencies at the 23-percent level compared to theoretical values of 28 percent, the technical device problems center more around optimization rather than feasibility studies.

#### MANY COMPANIES HAVE GaAs TECHNICAL BASE

From the semiconductor industry there has come a wealth of material knowledge and device experience from production of light-emitting diodes (LEDs). This bank of knowledge, however, is not as extensive as in the case of silicon technologies. Nonetheless, there does exist a formidable number of companies capable of contributing to the GaAs technology base (i.e., 18 IC firms, 22 discrete firms, 14 optoelectronic firms, and 6 to 10 photovoltaic firms).

The most prominent commercial organizations in pursuit of single-crystal GaAs photovoltaic devices include IBM, Varian, Rockwell, Hughes, Harris, HP, and Bell Labs. Their primary interest has been in heterojunction and P-N junction devices. The Schottky barrier devices have not received as wide attention, but significant work in this area is being done at IBM, JPL, and Southern Methodist University (SMU). MIT Lincoln Lab and several universities throughout the country also have GaAs research programs underway. One of the most dominant forces for GaAs development has been the government-operated Sandia Laboratory in Albuquerque, New Mexico.

#### SINGLE-CRYSTAL GaAs MATERIAL EXPENSIVE AND BRITTLE

Based on the experiences in the semiconductor industry, two significant characteristics concerning GaAs material are readily apparent. First, the production of GaAs substrate material is very slow, cumbersome, and expensive. Second, the GaAs material is extremely brittle, implying expensive and precise handling equipment in the mass-production mode.

Gallium in its proper form can be very expensive, depending upon the epitaxial process selected. For instance, gallium metal of electronic grade costs \$0.80 per gram, but goes to \$80 per gram in the form of  $\text{Ga}(\text{CH}_3)_3$  for use in the metal organic growth process. This would have to be reduced by perhaps an order of magnitude for economic viability. Fortunately, the metal organic growth process is a highly efficient (80 percent) process for converting the gallium to usable substrate material. The reduction of the cost of gallium may require a program similar to the silicon cost reduction programs presently under the direction of JPL.

Experiences from pilot production lines should provide the necessary insight for the proper handling equipment. Present-day semiconductor operations for light-emitting diodes still contain significant labor content due to the material's brittle characteristics. Sufficient volume production has not occurred to warrant the development of extensive handling equipment.

#### SCALE-UP OF OPERATIONS WILL NOT BE EASY

Because there has not been any scale-up of the processes, the necessary quality and process control parameters to ensure reproducibility and uniformity have not been identified. It is assumed that standard semiconductor industry standards of cleanliness and process controls will suffice. This can only be verified at the pilot-line level of operation.

Any scale-up attempts of the process will be hindered by the crystal-pulling and epitaxial growth processes. Both are extremely sensitive to the presence of moisture and oxygen. The high pressures involved in the crystal-pulling operation will require strict safety procedures. These should be available through LED production facilities. While these procedures may not significantly influence a pilot production line, they could have far-reaching implications where several dozen crystal pullers are in one production area.

Scaling up of the epitaxial growth process appears to favor the metal organic growth (MOG) process. The desire would be to accomplish a continuous-flow process. The LPE process may have several restrictions in meeting this desire, while the VPE and MOG processes hold greater promise of compliance.

The remaining processes are not expected to be a severe problem at the pilot-line stage, but could represent significant engineering hurdles at the mass-production stage.

While reproducibility of heterojunction and P-N junction devices appears to be possible, it has not been fully demonstrated. Sufficient evidence does exist, however, in association with certain structures (i.e., AlGaAs/GaAs) that pilot production lines could be established that could consistently produce product at acceptable yields. The Schottky barrier structures, however, do not at this point appear sufficiently developed to warrant such investments of capital.

#### PRESENT CELL SIZE SUFFICIENT

Efforts to increase cell sizes will not be a dominant issue of most future programs. Cells in excess of 1.5 cm<sup>2</sup> in area are not likely to be needed, since refractive means of insolation concentration will be the most predominant. This is in contrast to the approach taken by solar thermal concentration developments, in which reflective insolation concentration dominates designs. The present state of technology development can produce single-crystal GaAs solar cells in the 0.5 to 1.5 cm<sup>2</sup> area sizes.

## SUMMARY OF MAJOR BARRIERS TO COMMERCIALIZATION

### TECHNOLOGY BARRIERS

The following is a summary of the major technology barriers that must be resolved before large-scale industrialization can be possible:

- Determine quantitatively the best epitaxial deposition method; options include vapor phase, liquid phase, and metal organic approaches
- Cost reduction of GaAs substrate material; may require similar cost reduction program as for present-day single-crystal silicon
- Optimization of structures required
  - Doping and defect mechanisms are not fully understood or characterized
  - Improvement in minority carrier lifetime
  - Improvement needed in series resistance of metal grid contacts
- Industry sources indicate higher efficiencies are needed if bulk energy markets are to be supplied; need development of advanced systems such as high-efficiency cascade or multijunction cells

### MANUFACTURING BARRIERS

A scaling up of the present laboratory processes will require efforts devoted to:

- Development of specialized handling equipment due to the brittle nature of GaAs material
- Development of large-scale epitaxial equipment once technology issue is resolved
- Establishment of process and quality control methods to ensure reproducibility and uniformity
- Establishment of specialized controls to account for the toxic nature of arsenic compounds

## OTHER RELATED INFLUENCES TO COMMERCIALIZATION

There are other issues that could influence the development pace of single-crystal GaAs devices both positively and negatively. These include:

- Material availability, especially gallium; is thought to be sufficient, but must be quantitatively confirmed
- Field reliability data is lacking; data is insufficient to confirm or deny existence of long-term latent failure modes
- Development pace of low-cost, high-concentration ratio collect designs
- Lack of multiyear government contracts can limit industry's capital commitment to single-crystal GaAs production scale-up efforts
- Availability of commercial markets willing to accept concentrator systems; to date only government contracts make up the market



### 3.5 POLYCRYSTALLINE GALLIUM ARSENIDE

#### TECHNOLOGY DESCRIPTION

The comments, issues, and barriers associated with single-crystal gallium arsenide solar cells in general apply to the polycrystalline structures. There are, however, additional problem areas that arise due to the special nature of the polycrystalline structures that compound and limit their development pace when compared to the single-crystal structures. This section will deal primarily with those added complications.

One of the reasons for developing thin films of polycrystalline GaAs for photovoltaic cells is derived from the material's inherently high absorption coefficient. This allows the energy to be absorbed in a very thin layer of material. This conceivably could result in far less material required for cells than in the case of polycrystalline silicon devices. This assumes comparable efficiencies can be obtained.

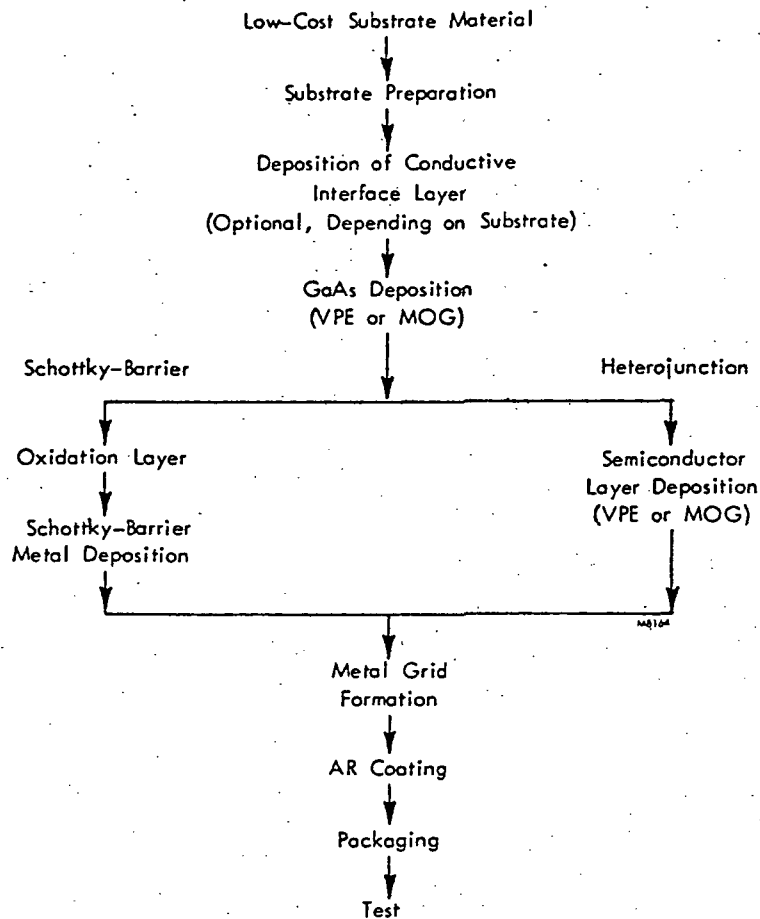
#### SUBSTRATE MATERIAL CAN INFLUENCE CELL CHARACTERISTICS

A generalized manufacturing flow chart for polycrystalline GaAs cells is shown in Figure 3.16. The selection of a substrate material is based upon a compromise of various characteristics, including:

- Material cost--must be inexpensive
- Availability--should be commercially available from several sources to reduce development costs
- Chemically inert--reduce autodoping and interaction with subsequent process steps
- Good conductivity--will act as an electrical contact
- Thermal coefficient of expansion--must closely match thermal expansion characteristics of subsequent layers

The most commonly used materials are graphite and tungsten, but other potentials include various metals, molybdenum, and glasses coated with metals, graphite, tungsten, or molybdenum. The substrate preparation is principally a cleaning or degreasing operation, followed by a high-temperature firing.

FIGURE 3.16  
MANUFACTURING FLOW CHART FOR POLYCRYSTALLINE  
GaAs PHOTOVOLTAIC CELLS



Depending on the substrate material used, a thin interface material, typically germanium or tungsten, may be needed to ensure low contact resistance, good thermal contact, and improved grain characteristics of the subsequent GaAs layer. This interface layer is deposited by vacuum evaporation with the substrate material elevated in temperature. The layer deposited is polycrystalline and very often must be recrystallized to form larger grain sizes. This is done by way of a localized heat source or a scanning laser. The process is somewhat slow (3 to 4 cm<sup>2</sup> per minute).

#### PROBLEMS WITH MAINTAINING QUALITY OF GaAs LAYER

Deposition of the GaAs layer is usually by the vapor phase epitaxial (VPE) process, in which gallium, hydrogen chloride, arsine, and hydrogen react in a temperature-controlled environment. Other processes used in the past but giving poorer results include sputtering and flash evaporation. More recently, the metal organic growth (MOG) process has been found to offer greater capabilities over the VPE process. A major advantage of the MOG process is that it allows the growth of heterojunction structures in a quasi-continuous process. This would be far more complex in a VPE system. Bell Labs has demonstrated a VPE system for heterojunction formation, but it would be difficult to convert it to a continuous-flow process.

A significant problem affecting reproducibility and yield is the formation of pinholes in the GaAs layer. These pinholes form during the growth process and appear to be dependent upon growth conditions and the substrate material. Microcracks are also present on some samples. This is believed to be caused from the same conditions contributing to the pinholes. The problem associated with the pinholes and microcracks is that shorts or low resistant shunts are formed when subsequent heterojunction layers are deposited.

#### SCHOTTKY BARRIER AND HETEROJUNCTIONS MOST COMMON CELL STRUCTURES

For the Schottky-barrier (SB) structures, the GaAs layer is oxidized in a mixture of argon and oxygen, followed by an oxygen and water vapor environment. The thickness of the oxidation layer is critical to the device performance. As the layer increases in thickness, the series resistance rapidly increases, which will negatively affect power output and efficiency. If the oxide layer is too thin, the  $V_{OC}$  will not be maximized. Thickness of the layer is thus a compromise of several parameters.

The SB metal deposition step is a standard semiconductor evaporation process. Gold, silver, platinum, or a number of other metals may be used. The thickness of this metal layer is from 50 to 100 angstroms.

The heterojunction structures are formed by a VPE or MOG deposition of a semiconductor compound material, such as GaAlAs, AlAs, or  $SnO_2$ . A major technical problem associated with these layers is their high spreading resistance, which has been a significant cause of low conversion efficiency. The rough surface of these layers is also one of the principal causes of high contact resistance and reduced power output of polycrystalline GaAs heterojunction cells.

#### P-N JUNCTIONS NOT AS SUCCESSFUL

Attempts at forming polycrystalline P-N junction cells have in general not been successful. During the diffusion process, the dopants rapidly diffused along the grain boundaries of the GaAs layer, causing leakage paths and shorts. When P-N junctions were formed by the VPE process, extremely high sheet resistances were encountered in the deposited layer. Significantly more work will be needed in understanding grain boundaries and how to work with them before P-N junction structures in any polycrystalline material will be successful.

#### FINAL PROCESS STEPS COMMON TO ALL CELL STRUCTURES

For both the SB and heterojunction structures, the metal grid formation process is essentially the same. The most commonly used laboratory method at present is evaporation of the grid metal through a mask. This will have to be replaced by a more economical continuous-flow method in time, but for laboratory samples it is quite sufficient.

The anti-reflective (AR) coatings used include oxides of tantalum, niobium, antimony, or titanium. These coatings can often double the cell efficiency, especially at efficiency levels below 5 percent.

Cross-sectional views of typical SB and heterojunction structures are shown in Figure 3.17 and 3.18, respectively. The GaAs layer is usually composed of a heavily-doped region next to the germanium or tungsten layer for contact purposes and more lightly doped in the remaining portion of the layer. Doping is typically accomplished through the use of zinc dopants.

FIGURE 3.17  
CROSS-SECTIONAL VIEW OF SCHOTTKY BARRIER  
POLYCRYSTALLINE GaAs CELL

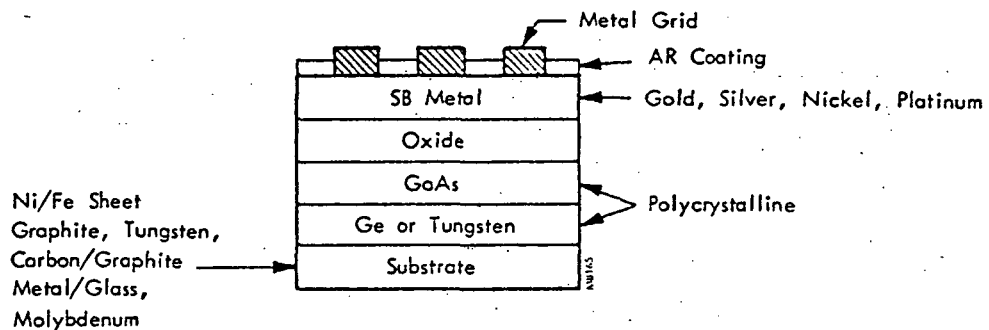
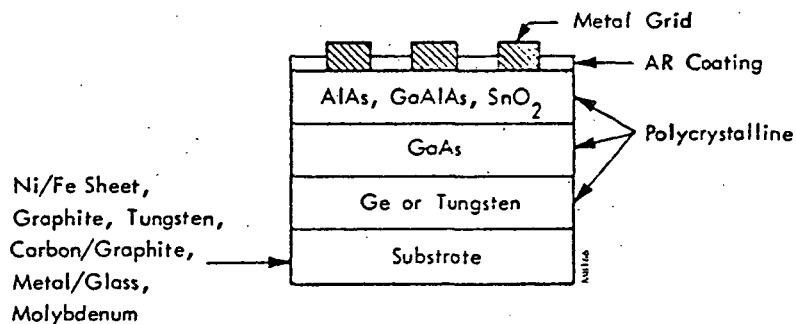


FIGURE 3.18  
CROSS-SECTIONAL VIEW OF HETEROJUNCTION  
POLYCRYSTALLINE GaAs CELL



## TECHNOLOGY PERFORMANCE CHARACTERISTICS

### GRAIN SIZE AND BOUNDARY CONDITIONS DOMINATE CELL CHARACTERISTICS

The primary structural characteristic that determines cell performance in polycrystalline GaAs is grain size and grain boundary conditions. At present, the open circuit voltage ( $V_{OC}$ ) and fill factor (FF) are severely limited by conduction mechanisms related to the grain boundaries. These mechanisms are not clearly understood or controllable.

The short-circuit current density ( $J_{SC}$ ) is directly associated with grain size. As the grain size increases, so does  $J_{SC}$ . Once grain sizes of  $100\text{ }\mu\text{m}$  or larger are obtained, the dependence of  $J_{SC}$  on grain size diminishes rapidly. With such grain sizes,  $J_{SC}$  reaches values comparable to these found in single-crystal structures.

Grain size in the GaAs layer is dependent upon the substrate material and the interface layer of germanium or tungsten. The larger the interface layer grain size, the larger the GaAs grains. This is the principal reason for recrystallizing the germanium after its deposition.

Grain size can also be increased with thicker layers of GaAs. Beyond film thicknesses of  $10\text{ }\mu\text{m}$ , the grain size is approximately equal to 25 percent of film thickness. However, this defeats the purpose of thin films; namely reduced film thicknesses for reduced costs. Below  $10\text{ }\mu\text{m}$  thicknesses, grain size varies from 50 to 100 percent of film thickness. Most studies today indicate that grain sizes of 15 to  $20\text{ }\mu\text{m}$  as a minimum will be needed for cell efficiencies in excess of 10 percent. The only cells produced on polycrystalline GaAs with efficiencies beyond 10 percent have been on material having grain sizes of greater than  $100\text{ }\mu\text{m}$ .

### PERFORMANCE PARAMETERS VARY SIGNIFICANTLY

Efficiency conversion of polycrystalline GaAs cells ranges from 2 to 8 percent. Significant variations in the distribution of cell efficiencies are seen at the high end of this range. The most consistent results have been obtained at SMU with efficiencies at the 6.5 percent level. The 8 percent cells were obtained at JPL, but with great variability from cell to cell. In general, efficiency is tied to grain size and GaAs growth conditions.

Values of  $V_{OC}$  range from 0.4 to 0.6 volts, while fill factors have centered around 0.60, with some reported as high as 0.63. If grain sizes beyond  $100\text{ }\mu\text{m}$  are used, then fill factors near 0.74 are observed.

The short-circuit current ( $J_{SC}$ ) has shown tremendous variability, depending upon grain size. Values range from  $12.5\text{ mA/cm}^2$  on very fine grain size ( $<5\text{ }\mu\text{m}$ ) material to double that on  $100\text{ }\mu\text{m}$  grain size material.

#### ULTIMATE BENEFIT COULD BE LIMITED

The ultimate real advantage of thin-film GaAs is its hoped-for low cost due to reduced material requirements compared to single or polycrystalline silicon. With large grain sizes of 100  $\mu\text{m}$  or more, the cell efficiency is not expected to exceed 14 to 16 percent. With grain sizes in the 20  $\mu\text{m}$  range, efficiencies will be significantly lower than this. Polycrystalline silicon cells are expected to be in the 10 to 12 percent range. For the expected added efficiency of only 4 percent maximum, the costs of thin-film gallium arsenide will have to be reduced significantly if it is to compete economically with polycrystalline silicon. This would raise the question as to the real future for thin-film GaAs if success is forthcoming with polycrystalline silicon.

#### STABILITY AND RELIABILITY NOT YET ESTABLISHED

Stability of present-day polycrystalline GaAs cells is virtually unknown. The SB structures are subject to degradation of the oxide layer regardless of which material base is used. Humidity, oxygen, and temperature can change the oxide density and composition. Ionic contamination is known to influence oxide characteristics also. Thus any SB structure will require significant packaging capabilities to protect the cell from environmental conditions. The heterojunction and any future P-N junction structures will have the advantage of having the junction buried in the bulk material region, making it much less sensitive to packaging and environmental conditions.

The development of these cell structures is not yet sufficiently advanced to warrant any elaborate field reliability testing. Significantly larger technical problems in film growth must first be resolved.

#### COMMENTARY ON COLLATERAL TECHNOLOGY REQUIREMENTS

##### ENCAPSULATION/PACKAGING REQUIREMENTS

Little has been attempted in developing packages for polycrystalline GaAs cells. Most laboratory samples are kept in inert atmospheres for storage and are not completely encapsulated. Often the AR coatings are not even applied. Emphasis has been on material and cell structure development with little intent directed toward completed devices.

The ultimate intent is to develop a continuous-flow process in which the cell structure and the packaging materials are functionally integrated. This concept applies to virtually all the thin-film technologies. Where the unique differences are between the various technologies will depend upon cell characteristics and their reaction to the environment. Development in this area will remain relatively dormant for some time until cell structure developments are more advanced.

## ENVIRONMENTAL IMPACTS ON CELL RELIABILITY

Two effects are known concerning polycrystalline GaAs structures. First is that the oxide layer of the SB structures is subject to oxygen, moisture, temperature, and ionic contamination. Second is that GaAs will oxidize as does silicon.

The ultimate effect of these two characteristics is not fully comprehended yet due to the early stage of development for this technology base. It does imply that packaging requirements will have to be moisture-resistant, if not hermetic. The heterojunction structure should be inherently more resistant to environmental effects than the SB structure, since the junction is buried within the bulk material area. P-N junctions, if possible, would be even better in this respect.

Thermal shocks due to severe changes in temperature as well as continuous thermal cycling has not been applied to present cell designs to determine their effects. These environmental conditions could have severe effects on grain boundaries and interfaces between layers.

## ENVIRONMENTAL IMPACT OF MANUFACTURING PROCESS

Reference should be made to the single-crystal GaAs section for discussions on environmental impacts of gallium and arsenic production and the handling of arsenic compounds in a production facility. Thin-film technologies do not rely upon high-pressure growth processes for the GaAs material as in the single-crystal case. The GaAs material is produced instead by the reaction of gases that are at relatively low pressures. Explosions are far less likely in this case. There do exist, however, many more opportunities for leaks, as the growth equipment contains many pipe joints and connections.

Methods for handling the waste products from the deposition processes are well developed in the semiconductor industry. If a large-scale production facility were implemented, it would cause concern not from what was needed to be done, but about how to handle the significantly larger quantities of waste material.

The proper OSHA standards would have to be maintained. Even though the danger of an explosion is significantly reduced, there still lie the inherent dangers associated with handling toxic arsenic compounds.

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No large-area cells have been produced, especially with grain sizes in the 15 to 20  $\mu\text{m}$  range. Cell sizes have varied from 0.03  $\text{cm}^2$  to 9  $\text{cm}^2$ , with typical values in the 1  $\text{cm}^2$  region. This is, however, understandable, considering the level of development of this technology base. Until the more basic questions have been resolved, there will be few, if any, attempts at large-area cells.

## SUMMARY OF MAJOR BARRIERS TO COMMERCIALIZATION

### TECHNICAL BARRIERS

The following fundamental technical barriers must be resolved before a scaling-up of laboratory processes is applicable:

- Selection and characterization of compatible substrate materials
- Selection of proper substrate interface material and its growth conditions
- Selection of GaAs layer growth process; need to develop process to grow 15 to 20  $\mu\text{m}$  grain size with 5 to 10  $\mu\text{m}$  film thicknesses
- Identification of inherent failure modes
- General understanding of basic mechanisms associated with the growth, control, and electrical contact of polycrystalline structures

### MANUFACTURING BARRIERS

Little can be constructively stated at this point concerning potential manufacturing barriers, since the process details are not even remotely finalized or reduced to a limited set of options. In general, they will be associated with:

- Cost reduction and supply of gallium, arsenic, and substrate material
- Safety standards

- Equipment scale-up of layer growth and deposition chambers
- Low-cost metal grid process
- Package and cell functional integration

#### OTHER RELATED INFLUENCES TO COMMERCIALIZATION

Development of this technology base can be influenced either negatively or positively by other related influences. These would include:

- Development pace and ultimate cost/performance characteristics of polycrystalline silicon cells
- Nature of inherent reliability failure modes and the impact of the environment upon them
- At present, a limited number of persons and companies are involved in this technology base and its development; this could limit the ultimate development pace

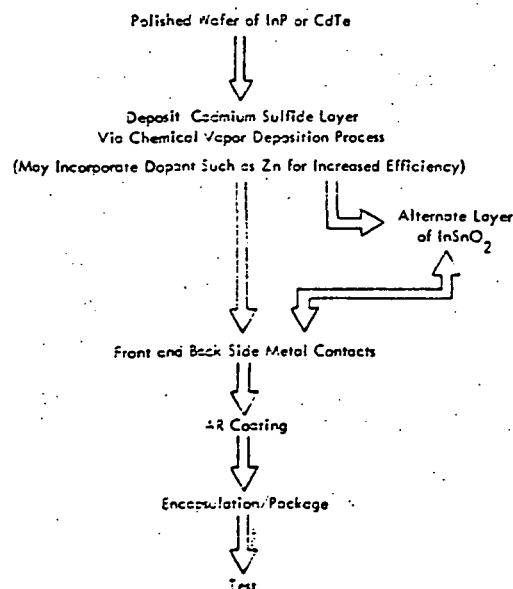
### 3.6 SINGLE-CRYSTAL CADMIUM SULFIDE

#### TECHNOLOGY DESCRIPTION

The single-crystal cadmium sulfide (CdS) structures are generally obtained through the growth of a CdS layer on a single-crystal substrate material, such as indium phosphide (InP) or cadmium tellurium (CdTe). These structures are heterojunctions (junctions formed between two different materials). No classical P-N junction structures as in single-crystal silicon have evolved in any of the CdS-based approaches.

A generalized flow chart for the production of a single-crystal CdS photovoltaic cell is shown in Figure 3.19. The substrate material is produced by similar ingot pulling processes used in the single-crystal silicon technology base. These processes can, however, be far more complex than in the case of silicon. For instance, the ingot growth chamber for InP must be built to withstand several hundred atmospheres of pressure compared to the slight vacuum used for silicon growth. Consequently, the substrate materials are often far more expensive than silicon and availability is extremely limited, since few, if any, organizations are equipped to mass-produce such material.

FIGURE 3.19  
MANUFACTURING FLOW CHART  
FOR  
SINGLE CRYSTAL CADMIUM SULFIDE  
PHOTOVOLTAIC CELLS



After proper surface preparation of the substrate, the cadmium sulfide layer is deposited by sputtering, vacuum, or spraying techniques to produce a single-crystal heterojunction device.

A thin, transparent layer of indium-tin-oxide is then deposited, followed by the metal contacts, an anti-reflective coating, and appropriate packaging. A variation in the structure in which the substrate material is single-crystal CdS and a thin layer of CdTe is deposited by way of a vapor transport process is possible. Performance of such cells has been inferior to the other described processes, however.

Cross-sectional views of the completed structures are shown in Figure 3.20a and 3.20b. The CdS layer may be composed of a graded dopant profile in which the top portion is highly doped for contact purposes. For increased efficiency purposes, zinc (Zn) may be introduced into the CdS layer also.

Several other substrate materials are being investigated presently, including GaAs and Ge. Results have not been satisfactory due to thermal mismatch and subsequent cell cracking.

FIGURE 3.20a  
CROSS-SECTIONAL VIEW OF SINGLE-CRYSTAL CdS/InP SOLAR CELL

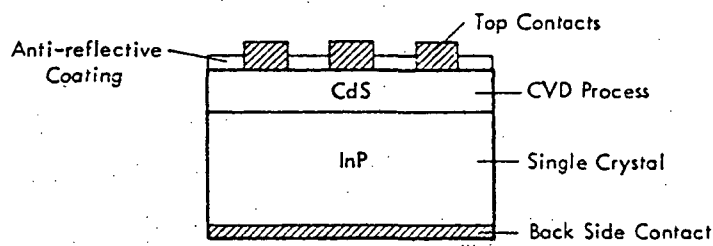
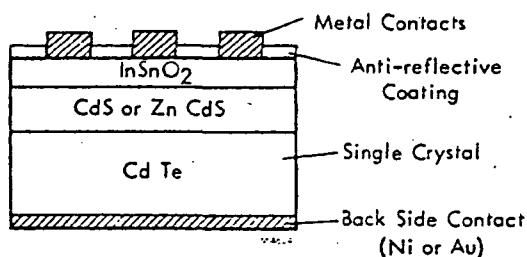


FIGURE 3.20b  
CROSS-SECTIONAL VIEW OF SINGLE-CRYSTAL CdS/CdTe SOLAR CELL



## TECHNOLOGY PERFORMANCE CHARACTERISTICS

Little is known about the true characteristics of single-crystal CdS layers. Compounding the investigations is the fact that heterojunctions are in general understood less than P-N junction structures. Limitations on the various photovoltaic cell characteristics are subsequently not well-documented or well-known.

One of the primary reasons for pursuing single-crystal structures is the identification of material properties and knowledge of cell characteristics that could be transferable to the more economic, thin-film, polycrystalline structures. Fundamental studies are thus often pursued in this area, even though no commercial product is likely to ever evolve.

More effort has been directed at the InP/CdS cell than the CdTe, CdZnTe, or the more exotic CuInSe<sub>2</sub>/CdS cells. The range and typical values of short circuit current density ( $J_{SC}$ ), open circuit voltage ( $V_{OC}$ ), fill factor (FF), and efficiency ( $\eta$ ) for InP/CdS cells are shown in Table 3.3. While typical efficiencies of 12 percent have been obtained on InP/CdS cells, the maximum reported for CdTe/CdS cells is 8 percent. Though not yet demonstrated, the CdZnTe/CdS cells are expected to have maximum efficiencies of 15 percent.

TABLE 3.3  
CHARACTERISTICS OF InP/CdS CELLS

Parameter	Range	Typical
$J_{SC}$	13-30 mA/cm <sup>2</sup>	25 mA/cm <sup>2</sup>
$V_{OC}$	0.36-0.72 volts	0.61 volts
FF	0.55-0.66	0.59
$\eta$	3%-15%	12%

The efficiency of InP/CdS cells is reported to be limited primarily by the quality of the InP substrate material. This material is extremely expensive; and as the quality of requirements is increased for improved cell performance, the price will rapidly increase. Efficiency is also limited by lattice mismatch of the heterojunction materials and by defects at the junction interface.

At present, the single-crystal CdS-based cells appear very stable. There is no field or long-term reliability data to support this, however. Few completed cells have been made. The intent of virtually all present development activities is to investigate and characterize cell and material parameters. There has not been to date a deliberate attempt to commercialize these structures.

#### COMMENTARY ON COLLATERAL TECHNOLOGY REQUIREMENTS

There have been no attempts to identify problems associated with packaging, manufacturing scale-up, environmental impacts, repeatability, and other associated areas beyond the basic fundamentals of the cell technology.

One of the principal problems to be faced by a scale-up of InP/CdS production will be the development of sufficient InP substrate production equipment. This is by far more limited today than was silicon substrate production equipment when the National Science Foundation first began pursuit of photovoltaics in the early 1970s. In addition, the equipment is much more complex due to the high pressures involved.

The availability of Te, In, and Cd must also be verified. Currently the US imports 65 percent of all its cadmium ore and metal. This could lead to potential problems if a significant photovoltaic demand for Cd should occur. Indium, while more plentiful in the earth's crust than Cd, is less developed as a commercially available material. The same can be stated for tellurium.

The environmental impact of Cd production is associated with its admission into the air. The Cd used is in the form of a powder that can easily become airborne if not handled properly. The constant inhaling of such powder can result in respiratory complications and hypertension. Cadmium is a major source of yellow pigment for the paint industry. As a result, chemical companies, such as Hercules Power, have extensive experience in the handling, safety, and environmental impact of cadmium powder. This base of experience could be used to establish the proper environmental controls for cadmium within a photovoltaic laboratory or manufacturing facility.

The present JPL programs in encapsulation, packaging, testing, and metal grid formation should be directly applicable to this technology base. There is, however, no assurance that some unique characteristics of this technology might not require specialized solutions in these program areas.

## STATE OF DEVICE TECHNOLOGY

### MATURITY LEVEL

The single-crystal cadmium sulfide technologies are presently in the research stage. Development of reproducible and usable devices is several years away, if ever. Virtually all efforts are being directed at fundamental understanding of material, junction, and doping parameters.

Hughes, Bell Labs, and Rockwell are industry leaders in developing knowledge of the InP/CdS structures. The University of Illinois is also pursuing basic studies in this area. OCLI and Stanford have devoted limited efforts to the CdTe/CdS area. None of these organizations have produced anything but limited quantities of such structures, and even fewer have actually been packaged for complete testing.

Reproducibility is often lacking in the laboratory processes. In addition, the photovoltaic effect is not fully understood or characterized. The effect of dopants upon junction properties is also lacking at this time. The size of functional cells is at best only a few  $\text{cm}^2$  in area, and often they are no larger than a few  $\text{mm}^2$ .

## SUMMARY OF MAJOR BARRIERS TO COMMERCIALIZATION

### TECHNICAL BARRIERS

The present identified technical barriers include:

- Need for better understanding of photovoltaic effect
  - Heterojunctions in general
  - InP/CdS and CdTe/CdS in particular
- Improvement in quality and understanding of junction interface area

- Development of doping techniques and characterization of dopant effects
- Identification of impact of substrate material characteristics
- General reduction in material defect levels
- Nonrepeatability of laboratory processes

With continued development of cell knowledge, other more focused technical barriers will be identified.

#### MANUFACTURING BARRIERS

The present state of development of this technology base has not required serious concern over manufacturing barriers. In fact, no serious attempts at commercial development are contemplated. This technology has been and will continue to be pursued for the purpose of obtaining material and basic operating mechanism information.



### 3.7 POLYCRYSTALLINE CADMIUM SULFIDE

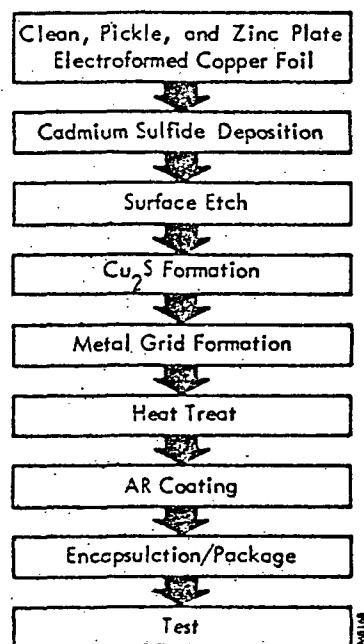
#### TECHNOLOGY DESCRIPTION

The polycrystalline thin-film photovoltaic cell technologies have over the years attracted the greatest attention in the cadmium sulfide (CdS) area. The principal reason for this is the potential of a low-cost continuous process that uses "off-the-shelf" type equipment and well-known manufacturing techniques.

The technology being pursued is heavily based upon that pioneered by the Clevite Corporation. Each of the present organizations devoting efforts to this technology field have explored many variations to the original process. However, the particular technology base that virtually all efforts are now directed toward is the CdS/Cu<sub>2</sub>S structure.

A generalized manufacturing flow chart of the CdS/Cu<sub>2</sub>S process is shown in Figure 3.21. The process begins with a suitable substrate material such as Kapton, copper foil, thin sheet of a steel alloy, or a thin glass sheet. The substrate materials must be cleaned and usually coated to enhance the adherence and electrical contact to the CdS deposited layer.

FIGURE 3.21  
MANUFACTURING FLOW CHART  
FOR POLYCRYSTALLINE CADMIUM SULFIDE PHOTOVOLTAIC CELLS



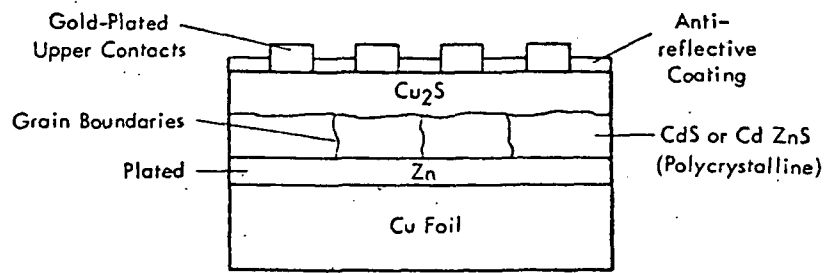
The process outlined in the flow chart is based on the use of an electroformed copper foil that has been cleaned and pickled in preparation for a zinc plating process. The zinc coating is required for adhesion of the cadmium sulfide (CdS) layer. The CdS deposition is performed in a vacuum chamber at elevated temperatures. While the vacuum vapor deposition chamber is the most expensive piece of equipment in the process area, the material consumption at this point is one of the lowest. Cadmium sulfide powder of proper quality ranges from \$5 to \$11 per pound. Only a thin layer ( $\approx 25 \mu\text{m}$ ), however, is required.

Following the CdS deposition, the structure is etched for surface texturing and then dipped in a copper ion solution for formation of the cupreous sulfide ( $\text{Cu}_2\text{S}$ ) layer. This is the basic structure to which a metal grid is applied along with anti-reflective (AR) coatings and the appropriate packaging.

The  $\text{Cu}_2\text{S}$  layer can also be applied by way of sputtering techniques. To date this has not proved as effective as the dip process. It has also been demonstrated that the two layers of the device can be sprayed onto a glass substrate. While this offers great economics, the efficiency is still less than 3 percent.

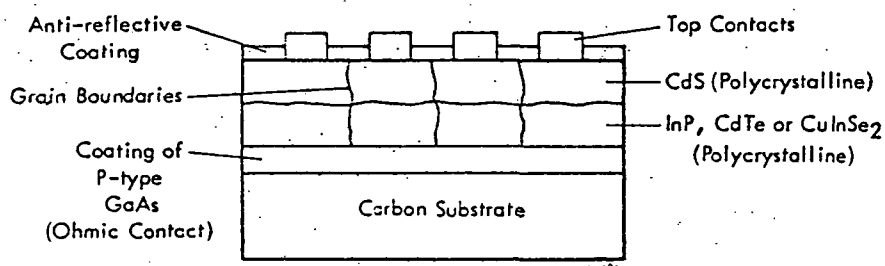
A cross-sectional view of the completed structure is shown in Figure 3.22. A slight variation of the process introduces zinc (Zn) as a dopant in the CdS layer. The zinc in theory should increase the open circuit voltage and a corresponding increase in efficiency ( $\eta$ ). At present, however, this expected increase is offset by a decrease in short-circuit current, and no significant gain in  $\eta$  is obtained. This deviation from expected theoretical results is believed to be associated with some manufacturing technique rather than an inherent structural limitation.

FIGURE 3.22  
CROSS-SECTIONAL VIEW OF POLYCRYSTALLINE  
CdS/ $\text{Cu}_2\text{S}$  SOLAR CELL STRUCTURE



Several other CdS-based structures have been investigated. A general description of them is shown in Figure 3.23. An inexpensive substrate to which ohmic contact can be made by various coatings is used to support CdS/InP, CdS/CdTe, or CdS/CuInSe<sub>2</sub> polycrystalline devices. Cell efficiencies have all been significantly lower than the CdS/Cu<sub>2</sub>S combination. Neither has a low cost of manufacturing characterized these processes as yet.

FIGURE 3.23  
CROSS-SECTIONAL VIEW OF POLYCRYSTALLINE  
CdS SOLAR CELL STRUCTURES



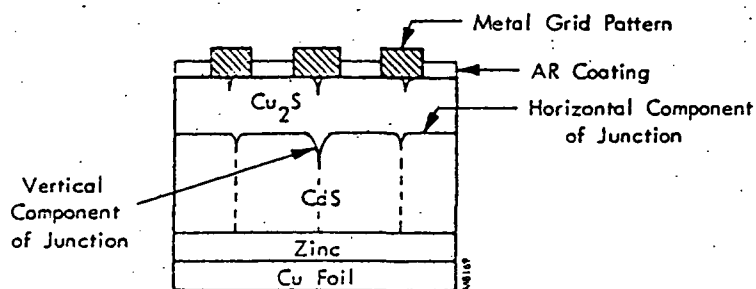
## TECHNOLOGY PERFORMANCE CHARACTERISTICS

A cross-sectional view of a CdS/Cu<sub>2</sub>S junction is shown in Figure 3.24. The junction is seen to have two principal components:

- A horizontal component
- A vertical component

The vertical component is developed primarily as a result of the etch following the CdS deposition and the natural grain boundary regions within the CdS layer. Reference will be made to these junction components in the following discussions of cell performance parameters.

FIGURE 3.24  
CROSS-SECTIONAL VIEW OF CdS/Cu<sub>2</sub>S STRUCTURE  
ILLUSTRATING  
JUNCTION COMPONENTS



## SHORT-CIRCUIT CURRENT DENSITY ( $J_{SC}$ )

The short-circuit current increases with an increase in junction area and a reduction of photon loss due to reflection at the outer surface of the  $Cu_2S$  surface. An increase in the surface texturing resulting from the etch process increases the vertical component of the junction area. This increases short-circuit current. At the same time, the etched surface reduces the photon losses at the surface. Losses at the surface are also dependent upon the AR coating used.

Thus short-circuit current can be increased by an increase in the vertical component of the junction area and improved AR coatings. Values in the past have ranged from 15 to 25  $mA/cm^2$  on the better cells. The best present-day laboratory samples are in the 25 to 28  $mA/cm^2$  range. Product from pilot and limited production lines are typically under 20  $mA/cm^2$ . The calculated theoretical limit is 35  $mA/cm^2$ .

## OPEN CIRCUIT VOLTAGE ( $V_{OC}$ )

The open circuit voltage can be increased by a reduction (opposite of  $J_{SC}$ ) of the vertical component of the junction area. This can be accomplished through a reduction or elimination of the surface texturing etch.

Values for  $V_{OC}$  have ranged from 0.45 to 0.52 volts. The calculated theoretical value is near 0.57 volts. The modified structure using zinc dopant in the  $CdS$  layer theoretically should have  $V_{OC}$  values of 0.7 to 0.8 volts. Present laboratory samples of such structures have typical values of 0.65 volts. However,  $J_{SC}$  is reduced to no more than 15  $mA/cm^2$ , which has held the overall  $\eta$  to near 6 percent instead of the expected 12 to 15 percent if  $J_{SC}$  and  $V_{OC}$  are fully maximized.

## FILL FACTOR (FF)

Besides its direct dependence upon  $J_{SC}$  and  $V_{OC}$ , the fill factor is limited by compensation centers that absorb carriers before they can be collected, the presence of metallic ions from the grid structure, and the series resistance of the bulk  $Cu_2S$  and  $CdS$  material. The compensation centers are irregularities of the  $CdS$  material that can be reduced in effectiveness via heat treatments in nonoxidizing environments, preferably hydrogen. The elimination of the metallic ions can be accomplished by using non-noble metal-grid structures. The optimizing of series resistance of the bulk materials will be through engineering evolution and characterization experiments.

The improvement in  $J_{SC}$  and  $V_{OC}$  as a result of variations in the vertical component of the junction will be a result of a compromise to maximize their product. This product will undoubtedly be a function of grain size. Thus a highly complex problem arises in maximizing FF.

Present values of FF in the laboratory range from 0.60 to 0.71. The calculated limit of FF is 0.81.

## EFFICIENCY ( $\eta$ )

The efficiency is directly related to  $J_{SC}$ ,  $V_{OC}$ , FF, the portion of cell surface available for collection, and reflectance characteristics of the cell surface. In addition, efficiency is limited by contact resistance and geometrical design of the metal grid system, decomposition of grain boundaries, and absorption coefficient of  $Cu_2S$  layer.

Historically, efficiencies have been in the 3.5 to 6.5 percent range. Recent laboratory samples have consistently been in the 7.5 to 8.5 percent range, with very limited sample quantities at the 9.1 percent level. The theoretical limit is not clearly defined or agreed upon. Estimates of the upper limit vary from 14 to 18 percent. The efficiency of the limited quantities of pilot or production line cells today have been less than 5 percent at the cell level and less than 3 percent after complete packaging.

## CELL STABILITY

The photovoltaic response in the cadmium sulfide/cuprous sulfide structure is heavily dependent upon the value of X in the  $Cu_xS$  portion of the junction. The value of X must be between 1.995 and 2.000. The closer to 2.000, the better the photovoltaic response of the junction. However, if X is equal to or exceeds 2.000, there will be no photovoltaic response. The level of response also decreases rapidly as X approaches 1.995.

The value of X is influenced primarily by process control parameters. Such parameters include the acidity and temperature of the copper ion solution, time of exposure to ion solution, and manufacturing techniques, including prior preparation of the CdS surface.

The growth of the  $Cu_2S$  layer is a result of cadmium atoms being replaced by copper atoms at the surface of the CdS layer. The copper in the  $Cu_2S$  layer has a higher affinity for oxygen than for sulfur. Consequently, the  $Cu_2S$  layer will rapidly convert to CuS

as the copper atoms are lost to form  $\text{Cu}_2\text{O}$  in the presence of oxygen (i.e., air and/or moisture). This will decrease the photovoltaic response of the junction significantly. It only takes a few atoms of oxygen to begin this degradation process. A proper atmosphere must thus be maintained at the surface if degradation is to be prevented.

If the  $\text{Cu}_2\text{S}$  has been degraded by the presence of oxygen, the effect can be reversed by placing the cell in the presence of hydrogen and heat. The oxygen attached to the copper atoms will disassociate and combine with the hydrogen and can be exhausted as water vapor. The released Cu recombines with  $\text{CuS}$  to form  $\text{Cu}_2\text{S}$ . The presence of heat simply speeds up the reaction. To prevent the recurrence of  $\text{Cu}_2\text{O}$  and the associated degradation, the cells must be kept in a non-oxygen environment.

## COMMENTARY ON COLLATERAL TECHNOLOGY REQUIREMENTS

### HERMETIC PACKAGE REQUIREMENTS

The presence of oxygen in most any form at the surface of the  $\text{Cu}_2\text{S}$  layer will cause rapid degradation of the cell's photovoltaic effect. To prevent this, the cadmium sulfide cell must be sealed in a hermetic package. This implies an expensive packaging scheme and a potential long-term reliability problem area for the field installations. Moisture-resistant packaging will not be sufficient for cadmium sulfide cells. Manufacturing techniques will be inherently difficult and costly, as they will have to ensure that no moisture or oxygen is entrapped during the final packaging operation.

### METAL GRID REQUIREMENTS

At present, most laboratory samples are produced using vacuum-deposited and etched gold or a gold-copper mixture as the top contact metal. Other grid materials used include copper compounds, gold-filled epoxies, and tin oxides. Most metallic grids result in high costs and potential reliability problems due to ion migration, especially along the grain boundaries of the  $\text{CdS}$  layer.

The desirable characteristics of the grid contact system are:

- Good ohmic contact to  $\text{Cu}_2\text{S}$  layer
- Good electrical conductivity
- Transparent to incident radiation to which the junction is responsive
- Stable composition
- Low in cost

A compromise of these characteristics will no doubt have to occur. Present metallic systems will ultimately be replaced by such concepts as tin oxides that can be sprayed onto the cell surface.

#### ENVIRONMENTAL IMPACTS ON CELL RELIABILITY

The most critical environmental impact on the performance characteristics of the cells will be from the presence of moisture and oxygen. Their influence will be dependent upon the integrity of the packaging scheme as to its long-term hermeticity capabilities.

Sufficient field data is lacking to determine if any other inherent failure mechanisms exist that are related to long-term environmental conditions. It would be safe to conclude that performance degradation mechanisms identified in association with packaging systems and package material deterioration characteristics in silicon-based photovoltaic products would also apply to the cadmium sulfide devices.

#### ENVIRONMENTAL IMPACT ON MANUFACTURING PROCESS

Cadmium is a by-product of zinc mining and smelting. Emissions of cadmium into the air at the refining plants as a result of large-scale cadmium sulfide photovoltaic production would be less than 5 percent of present-day emissions. This would thus not be considered a serious problem area.

The most serious potential environmental impact of the overall manufacturing process would be associated with emission of  $\text{CdS}$  fumes and dust. The form of  $\text{CdS}$  used for photovoltaic production is a powder that could easily become airborne if not handled properly. Since cadmium is a biologically nonessential element, the human body will store any quantities that may be inhaled. Continued intake of cadmium can result in respiratory complications and hypertension.

Other possible environmental impacts could result from the improper disposal of metal salt solutions used in the plating and etching processes. These potential water pollution problems can be avoided, however, if present-day OSHA regulations are followed.

#### IMPACT OF PRESENT JPL PROGRAMS

The technology development efforts at JPL in the area of encapsulation, metal grid structures, and packaging materials should be directly applicable to cadmium sulfide/cupreous sulfide photovoltaic structures. Additional requirements in the packaging areas would have to be added to the JPL program to account for the hermeticity requirements and the need to complete the packaging process in a non-oxygen atmosphere. Efforts directed at continuous-flow vacuum deposition equipment should also have direct application.

#### STATE OF DEVICE TECHNOLOGY

#### MATURITY LEVEL

Serious efforts have been applied to the understanding and development of polycrystalline cadmium sulfide photovoltaic cells for at least 20 years by various organizations, including the Harshaw Chemical Company, Clevite Corporation, Institute of Energy Conversion at the University of Delaware, SES (a Shell Oil subsidiary), Baldwin, Photon Power (a subsidiary of Societe Francis du Petrol and Libby-Owens Ford), Westinghouse, and several foreign organizations such as SAT, AEG-Telefunken, and International Research and Development Company. The CdS photosensitive characteristics have been known since the mid-19th Century. They have been applied to light-sensing applications only up until the last few decades. Even with this enormous background of knowledge, the CdS products have not lived up to expectations.

The activities at most of these organizations has either been discontinued or restricted to laboratory investigations. Attempts at SES to institute mass-production processes have not proven fruitful to date. Results at the Institute of Energy Conversion (IEC) have been the most encouraging at the unencapsulated device level, but completed devices for field testing have not emerged to any significant degree. The Photon Power process is still in the developmental stage. SES, IEC, and Photon Power are the three major organizations pursuing CdS technologies, but it appears unlikely that any of these groups will produce a product beyond the 3 percent efficiency level in the foreseeable future.



In summary, the polycrystalline CdS/Cu<sub>2</sub>S photovoltaic technology base must still be considered at the laboratory level. There does, however, exist some degree of knowledge available as to the real problems to be encountered at the pilot and production line level.

Other indications of the maturity level of a process include the number, consistency, and size of cells that can be produced. At present, the IEC process can reproduce 6 to 8 percent efficiency cells in the 10 cm<sup>2</sup> range that are sectioned into 1 cm<sup>2</sup> sections for further evaluation. Complete encapsulated cells are not generally available or attempted at present. Only a limited number (less than a dozen) of 9 percent efficient cells of 1 cm<sup>2</sup> each have been produced.

The Photon Power process produces 2 to 3 percent efficient cells in the 4 in<sup>2</sup> size consistently. Larger cell sizes of several ft<sup>2</sup> have been produced, but at lower efficiency levels (1 to 2 percent) and with less consistency.

Several thousand watts of 2 to 4 percent efficient modules have been produced by the SES process. They have been plagued, however, by severe field reliability problems. At present, these reliability and some internal yield problems are being investigated. While large area devices can be made, their consistency in production and expected reliability have restricted their commercialization.

## SUMMARY OF MAJOR BARRIERS TO COMMERCIALIZATION

### TECHNICAL BARRIERS

The following technical issues must be resolved before industrialization of sufficiently high-efficiency cells can be implemented:

- Selection of basic device process
  - Substrate material
  - Layer deposition method
    - Vacuum
    - Dipping
    - Sputtering
    - Spraying
- Doping techniques and influence of dopants

- Optimizing grain boundary composition
- Develop low-cost metal grid system and its proper ohmic contact characteristics
- Development of hermetic package and associated manufacturing techniques

#### MANUFACTURING BARRIERS

Once the basic technical barriers are resolved and sufficient understanding of the processes are established, the scale-up in manufacturing equipment and techniques will evolve as a critical issue. The present identifiable areas needing attention that are common to the various available processes include:

- Control of fume and powder cadmium emissions
- Control of waste etch and plating solutions
- Identification of manufacturing parameters that influence reproducibility

Depending upon which basic device process is selected, there could be equipment development problems in the areas of:

- Continuous-flow vacuum and sputtering deposition equipment
- Layer thickness control monitors
- General process control equipment.

#### OTHER RELATED INFLUENCES TO COMMERCIALIZATION

There are other items that could influence the development rate of the CdS/Cu<sub>2</sub>S processes both positively and negatively. These would include:

- Establishment of long-term field reliability data
- Application of present JPL programs
  - Encapsulation
  - Metal grid structures
  - Packaging materials
  - Continuous-flow vacuum deposition
- Commercial availability of cadmium

### 3.8 SYNOPSIS OF OTHER ADVANCED TECHNOLOGY OPTIONS

Many other single-crystal and polycrystalline advanced technologies exist. A partial list of such technologies is shown in Table 3.4, along with the best reported efficiency of conversions. This is by no means a complete list, but it does emphasize that many technology options are available.

TABLE 3.4  
SUMMARY OF OTHER ADVANCED PHOTOVOLTAIC SOLAR CELL TECHNOLOGIES

Structure	Crystalline Orientation of Substrate		Best Reported Efficiencies
	Polycrystalline	Single-Crystal	
Metal/CuO <sub>2</sub>		X	1%
CuO <sub>2</sub> /Si		X	1%
CdS/CuInSe <sub>2</sub>		X	12%
CdS/CuInSe <sub>2</sub>	X		3%-7%
CdS/CuInS <sub>2</sub>	X		3%-4%
CdS/InP		X	9%-14%
CdS/InP	X		< 2%
InSnO <sub>2</sub> /InP		X	9%-14%
InSnO <sub>2</sub> /GaAs		X	5%
InSnO <sub>2</sub> /Si		X	12%
InSnO <sub>2</sub> /Si	X		< 4%
InSnO <sub>2</sub> /CdTe		X	3%-8%
InSnO <sub>2</sub> /CdTe	X		2%
CdS/CdTe		X	8%
ZnO/CdTe		X	< 5%
InSnO <sub>2</sub> /CuInSe <sub>2</sub>		X	9%
InSnO <sub>2</sub> /CuInSe <sub>2</sub>	X		2%
In <sub>2</sub> O <sub>3</sub> /GaAs		X	< 2%
In <sub>2</sub> O <sub>3</sub> /InP		X	< 2%
In <sub>2</sub> O <sub>3</sub> /Ge		X	< 2%
In <sub>2</sub> O <sub>3</sub> /Si		X	< 2%
SnO <sub>2</sub> /Si		X	12%
SnO <sub>2</sub> /Si	X		< 10%
Metal/Zn <sub>3</sub> P <sub>2</sub>		X	6%
ZnSiAs <sub>2</sub> /Ge		X	< 1%
ZnSiAs <sub>2</sub> /GaAs		X	1%
Metal/WSe <sub>2</sub>		X	5%
ZnSSe/CdTe		X	Unknown
CdS/AgInSe <sub>2</sub>	X		Unknown
CdS/CuGaSe <sub>2</sub>	X		Unknown
CdS/CuInTe <sub>2</sub>	X		Unknown

There are several critical issues at stake with most of these possible technology bases. The issues center around:

- Availability of material
- Sufficient characterization data
- Sufficient resources--both economic and manpower

As can be seen in the list of other options, rare earth materials such as In, Se, and Te are commonly required. It is most likely that the extraction of large quantities of such materials will be expensive, if possible at all. Technically small quantities of these rare earth materials would be needed per unit area of cells. However, when considering that multigigawatts of photovoltaic devices will ultimately be required, the overall volume for these materials mushrooms beyond what could be reasonably extracted from the environment.

To date, the vast majority of these other options have very little accumulated characterization data. Little is known concerning:

- Theoretical limits of cell performance parameters
- Basic cell operating mechanisms
- Effects of grain boundaries, doping mechanisms, defects, growth conditions, etc.
- Stability and long-term reliability

Without such information, a judicious selection from the many possibilities cannot be made.

Since the possible options are so extensive in number, there is serious doubt that sufficient resources exist to support all of them simultaneously. Overall, the possibilities appear very low that any of these options will evolve into a major contributor to the photovoltaic industry commercial base, especially in the next five to ten years. Research activities in industrial laboratories and universities should continue, however, through the future years in hopes of finding that supreme material combination that best satisfies all commercial and energy supply requirements. /

## 4. Comparative Assessments

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### 4.1 TECHNOLOGY STRENGTHS AND WEAKNESSES

To assess the ultimate strengths/potentials and weaknesses/limitations of the advanced photovoltaic technology options, there must be a standard to which they can be compared. For the purposes of this report, the present-day single-crystal silicon wafer technology base is chosen.

It is assumed that this particular technology base will also continue to improve in both cost and performance characteristics. The comparisons made in this section are thus based on the future foreseeable potential of single-crystal silicon wafer (not ribbon or thin sheets) technology and not its present-day status.

The two principal characteristics that are expected to be significantly improved in the foreseeable future are efficiency and cost. Present-day efficiencies are reported in the range of 10 to 18 percent, with the typical being near 12 percent. This typical is expected to increase to the 15 percent level.

Selling prices are in the \$10/peak watt area where significant volumes are involved. The prices can, however, be two to three times that, depending on quantity and specifications. An order of magnitude improvement in prices is the best expected in the foreseeable future for the single-crystal silicon wafer technology.

The comparison to the single-crystal silicon wafer technology base of the six advanced technology options addressed by this study are shown in Table 4.1. A characteristic is considered an advantage for an advanced technology only if it is significantly better than for single-crystal silicon. Conversely, a disadvantage is listed only if it is considered significantly restrictive or limiting in nature compared to single-crystal silicon.

Note should be taken of the lack of significant advantages of polycrystalline GaAs and single-crystal CdS. There are significant disadvantages to single-crystal GaAs also, but its advantages offer excellent cost/performance possibilities in high-temperature concentrator applications. The technologies that offer a better

TABLE 4.1  
ADVANTAGES/DISADVANTAGES OF ADVANCED PHOTOVOLTAIC OPTIONS  
(Compared to Single-Crystal Silicon Wafer Technology Base)

Advantages	Disadvantages	Advantages	Disadvantages
Single-Crystal GaAs		Polycrystalline GaAs	
<ul style="list-style-type: none"> <li>• Response to available insolation is greater</li> <li>• Efficiencies significantly higher</li> <li>• Thinner layers of material required</li> <li>• High-temperature operation possible</li> </ul>	<ul style="list-style-type: none"> <li>• Material costs very high</li> <li>• Material very brittle</li> <li>• Crystal growth processes much slower</li> <li>• Equipment for crystal growth more complex due to high pressures</li> <li>• Higher potential for safety problems due to high pressures and toxicity of As compounds</li> <li>• Supply of Ga could become critical issue</li> </ul>	<ul style="list-style-type: none"> <li>• Growth processes should ultimately be faster and more efficient</li> </ul>	<ul style="list-style-type: none"> <li>• Presence of grain boundaries restricts performance</li> <li>• Quality of structure depends on substrate and interface materials and their preparation</li> <li>• Toxicity of As compounds presents possible hazards</li> <li>• Supply of Ga could become critical issue</li> <li>• Inherent practical efficiency is probably lower</li> <li>• Costs not expected to be lower</li> </ul>
Polycrystalline Silicon		Amorphous Silicon	
<ul style="list-style-type: none"> <li>• Requires less silicon</li> <li>• Potentially lower-cost processing</li> <li>• Applicable to continuous-flow processing</li> </ul>	<ul style="list-style-type: none"> <li>• Presence of grain boundaries restricts performance</li> <li>• Inherent practical efficiency is probably lower</li> </ul>	<ul style="list-style-type: none"> <li>• Lower-cost process</li> <li>• Requires less silicon</li> <li>• Applicable to continuous-flow processing</li> </ul>	<ul style="list-style-type: none"> <li>• Inherent practical efficiency is probably lower</li> <li>• Sensitivity to OH ions requires more stringent packaging</li> </ul>
Single-Crystal CdS*		Polycrystalline CdS	
	<ul style="list-style-type: none"> <li>• Substrate material more expensive</li> <li>• Depends on supply of rare earth elements</li> <li>• Substrates more complex to produce</li> <li>• Toxicity of Cd compounds presents possible hazards</li> </ul>	<ul style="list-style-type: none"> <li>• Lower-cost process</li> <li>• Less complex equipment needed, thus much simpler process steps</li> <li>• Applicable to continuous-flow processing</li> </ul>	<ul style="list-style-type: none"> <li>• Packaging restraints far greater</li> <li>• Toxicity of Cd compounds presents possible hazards</li> <li>• Availability of Cd more restrictive than silicon</li> <li>• Inherent practical efficiency is probably lower</li> <li>• Presence of grain boundaries restricts performance</li> </ul>

\*Included for completeness only; pursued at the laboratory level only for material and basic mechanism studies.

balance between advantages and disadvantages include polycrystalline silicon, amorphous silicon, and polycrystalline CdS. All three offer cost advantages and near-comparable efficiency levels. Each has its own unique disadvantages that may present significant barriers to overcome.

Another perspective can be gained concerning the inherent aspects of these advanced technologies by comparing them to each other without the use of an independent standard. Such a comparison is shown in Table 4.2.

This comparison is based on the ultimate capabilities of these advanced technologies and not their present-day status. Here it has been assumed comparable maturity levels exist and that packaging concepts are possible to overcome any identified impacts from the environment. This should not be interpreted as meaning necessarily inexpensive packaging.

Of the three technologies noted previously to offer reasonable cost advantages over single-crystal silicon, amorphous silicon stands out in this analysis as being the best of the three. Compared to amorphous silicon, polycrystalline silicon is limited by substrate and grain boundary influences. The polycrystalline CdS is restricted by material availability and grain structure. Amorphous silicon may ultimately have just as severe reliability and packaging problems as polycrystalline CdS.

TABLE 4.2  
COMPARATIVE ASSESSMENT OF ADVANCED PHOTOVOLTAIC TECHNOLOGY OPTIONS

Technology Base	Advantages	Disadvantages
Single-crystal GaAs	<ul style="list-style-type: none"> <li>• Highest practical and theoretical efficiency</li> <li>• Not influenced by grain boundaries as in polycrystalline-based technologies</li> <li>• High-temperature operation possible</li> </ul>	<ul style="list-style-type: none"> <li>• Costs limit application to concentrator systems</li> <li>• Greater toxicity problems than for silicon or CdS technologies</li> <li>• Processing not easily converted to continuous-flow methods</li> <li>• Ga supply potential problem area</li> </ul>
Polycrystalline GaAs	<ul style="list-style-type: none"> <li>• Slightly higher potential for efficiency than for polycrystalline silicon and CdS</li> <li>• Processing adaptable to continuous-flow methods</li> </ul>	<ul style="list-style-type: none"> <li>• Higher costs than polycrystalline silicon for limited increase in efficiency</li> <li>• Heavy influence of substrate and interface material on film quality and characteristics</li> <li>• Greater toxicity problems than for silicon and CdS technologies</li> <li>• Characteristics heavily influenced by grain structure</li> <li>• Ga supply potential problem</li> </ul>
Polycrystalline silicon	<ul style="list-style-type: none"> <li>• Material availability better than for polycrystalline GaAs and CdS</li> <li>• Material cost reductions of single-crystal silicon programs directly applicable; not so for GaAs or CdS</li> <li>• Process adaptable to continuous-flow methods</li> </ul>	<ul style="list-style-type: none"> <li>• Heavy influence of substrate and interface material on film quality and characteristics</li> <li>• Characteristics heavily influenced by grain structure</li> </ul>
Amorphous silicon	<ul style="list-style-type: none"> <li>• Film quality and growth not dependent on substrate materials</li> <li>• Material availability excellent</li> <li>• Efficiency potential as good as any thin-film technology base</li> <li>• Applicable to continuous-flow processing steps</li> <li>• Potential for lowest cost of thin-film processes</li> <li>• No grain boundaries to influence film characteristics</li> <li>• Material cost reductions of single-crystal silicon programs directly applicable</li> </ul>	<ul style="list-style-type: none"> <li>• Sensitive to OH ions, implies higher-cost packaging than for polycrystalline silicon</li> </ul>
Single-crystal CdS*	<ul style="list-style-type: none"> <li>• Cell performance not influenced by grain size or grain boundaries as in polycrystalline structures</li> </ul>	<ul style="list-style-type: none"> <li>• Depends upon very expensive substrate materials, elements of which are limited in availability</li> <li>• Performance limited by substrate material quality</li> <li>• Processing not easily converted to continuous-flow process</li> </ul>
Polycrystalline CdS	<ul style="list-style-type: none"> <li>• Potential for low-cost, thin-film processing methods</li> <li>• Process uses modified off-the-shelf equipment</li> <li>• Probably the simplest processing</li> </ul>	<ul style="list-style-type: none"> <li>• Cell parameters influenced by grain structure</li> <li>• Severe sensitivity to oxygen and moisture, requires more stringent packaging than polycrystalline silicon and GaAs</li> <li>• Availability of cadmium more restrictive than silicon</li> </ul>

\*Included for completeness only; this technology pursued only at laboratory level for material and basic mechanism studies.



## 4.2 PRESENT-DAY TECHNOLOGY COMPARISONS

The previous two comparisons have assumed ultimate capabilities of the various technologies. A comparison of the present status of these technologies based on maturity level, efficiency, and reliability and cell stability is shown in Tables 4.3, 4.4, and 4.5, respectively. These are based on summaries of the technology assessments of the previous chapter.

TABLE 4.3  
MATURITY STATUS OF ADVANCED PHOTOVOLTAIC TECHNOLOGIES

Technology	Maturity Status
Single-crystal GaAs*	Well developed
Polycrystalline CdS Polycrystalline Silicon Polycrystalline GaAs	In early stages of development
Amorphous Silicon	In embryonic stage of development
Single-crystal CdS	Undeveloped; pursued only for material and basic mechanism studies

\*Applicable only to concentrator system applications.

TABLE 4.4  
EFFICIENCY RANKING OF ADVANCED PHOTOVOLTAIC TECHNOLOGIES  
(Based on Present-Day Typical)

Rank	Technology	Present-Day Typical (%)	Estimated or Calculated Maximum <sup>1)</sup>
1	Single-crystal GaAs <sup>2)</sup>	20-23	28
2	Single-crystal CdS <sup>3)</sup>	8-12	--
3	Polycrystalline CdS	4-8	13-16
4	Polycrystalline GaAs	6-7	12-14
5	Polycrystalline silicon	3-7	10-14
6	Amorphous silicon	2-6	14-16

<sup>1)</sup>Except for single-crystal GaAs, none of these are firmly established.

<sup>2)</sup>Applicable only to concentrator system applications.

<sup>3)</sup>Included for completeness only; this technology pursued only for material and basic mechanism studies.

TABLE 4.5  
STABILITY AND RELIABILITY RANKING OF ADVANCED PHOTOVOLTAIC TECHNOLOGIES

Rank	Technology	Comment
1	Single-crystal GaAs	Stable; no serious long-term reliability problems identified.
2	Polycrystalline silicon	Stable; no identified long-term reliability problems; ion migration along grain boundaries may prove to be a problem.
3	Polycrystalline GaAs	Microcracks and pinholes form during growth that may indicate future problems.
4	Polycrystalline CdS	Degrades rapidly when exposed to oxygen and/or moisture; degradation reversible.
5	Amorphous silicon	Instability at higher efficiencies and large-area cells; sensitivity to OH ions.
	Single-crystal CdS	Not ranked due to lack of sufficient data; this technology pursued only for material and basic mechanism studies.

It is noted from these tables that single-crystal GaAs is the most mature of these advanced technologies, with the highest present efficiency, highest ultimate efficiency potential, and it is the most stable and reliable. The amorphous silicon technology is one of the least mature, has the lowest present efficiency, and is presently very unstable. Comparison of the present status of these two technologies should also be made with their ultimate potentials and limitations, as shown in Table 4.2. Amorphous silicon is shown to have outstanding future potential characteristics.

### 4.3 SUPPLY OF MATERIAL

Reference has been made several times in previous sections to the limitations of various materials associated with these advanced technologies. To add a quantitative perspective to these references, a listing of availability of critical materials is shown in Table 4.6.

TABLE 4.6  
AVAILABILITY OF MATERIALS IN THE EARTH'S CRUST  
(Parts per Million)

Technology Base	Materials in Advanced Photovoltaic Technologies		Materials Commonly Viewed as:			
			Plentiful in Availability		Rare in Availability	
	Materials	Availability	Material	Availability	Material	Availability
Single crystal and poly-crystalline GaAs	Gallium	19	Oxygen	456,000	Gold	0.004
	Arsenic	1.8	Silicon	273,000	Platinum	0.010
	Tin	2.1	Aluminum	83,000	Silver	0.080
	Aluminum	83,600	Iron	62,200	Iodine	0.460
	Carbon	180	Sodium	22,700	Thallium	0.700
	Tungsten	1.2	Hydrogen	1,520	Molybdenum	1.200
	Germanium	1.5	Sulfur	340		
Polycrystalline and amorphous silicon	Silicon	273,000	Carbon	180		
	Tin	2.1	Nickel	99		
	Carbon	180	Copper	68		
Single-crystal and poly-crystalline CdS			Lead	13		
	Cadmium	0.160				
	Sulfur	340				
	Copper	68				
	Indium	0.240				
	Selenium	0.050				

The availability of these materials is shown in parts per million of their presence in the earth's crust. This is not necessarily the only or most pertinent method to judge availability. The only true way to assess availability is to independently research each one and determine its state of commercial development, existence of domestic and foreign reserves, major influences governing its supply and distribution, and its cost to produce.

The point of presenting availability based on level of presence in the earth's crust is that if it does not exist in the earth's crust to any great degree, then it will always be a limited material, regardless of the state of commercial development. To add a comparative perspective to the availability levels shown for the required materials, the availability of some rare and readily available materials is also presented in Table 4.6.

Note should be taken as to the availability of silicon (273,000 ppm) compared to gallium (19 ppm), cadmium (0.16 ppm), indium (0.24 ppm), and selenium (0.05 ppm). While all of these materials are commercially available, the prospects of extremely low cost, high volume, and continued availability favor silicon-based technologies over those of gallium- or cadmium-based technologies. Gallium, for instance, is considered readily available today, but one-half to two-thirds of the US's supply must be imported. In effect, the US is not able to supply its own present commercial requirements of gallium. This could become a severe problem in increasing domestic availability and keeping costs within viable limits if large quantities were needed to support annual production levels of multigigawatts of photovoltaic product. The availability of materials thus favors silicon-based technologies.

Selection of a thin-film process requiring interface layers of tungsten or germanium or coating layers of tin oxides will also face some prospects of limiting due to material availability. This should be thoroughly analyzed before the final technology selection is made.

## 4.4 RELATIVE ECONOMIC COMPARISONS

### CAPITAL INVESTMENT RANKING

Another parameter by which to compare the advanced technology options is by their capital requirements to establish a development laboratory and production lines. No quantitative analysis was done in this area; thus judgmental treatment of extremely limited data heavily influences the rankings in the following assessments.

The capital investment ranking for the establishment of a laboratory for investigating the various technologies is shown in Table 4.7. The costs associated with a polycrystalline CdS laboratory range from \$75,000 to \$125,000. Except for an evaporator and a lamination press for final packaging purposes, the required equipment is relatively simple and inexpensive. Equipment associated with a single-crystal GaAs or CdS facility is far more complex and expensive. Costs can be as high as the \$300,000-\$400,000 range if crystal-pulling equipment is included. Diffusion furnaces and evaporators are also included as part of the facility.

TABLE 4.7  
CAPITAL INVESTMENT RANKING  
LABORATORY FACILITIES

Ranking (Increasing Expense)	Technology Base
1    Lowest cost	Polycrystalline CdS
2	Polycrystalline silicon
3	Polycrystalline GaAs
4	Amorphous silicon
5	Single-crystal GaAs
6    Highest cost	Single-crystal CdS

The other technologies range between these two levels of expense, the amorphous silicon being higher than the polycrystalline options at present due to limited availability of deposition systems and the high equipment modification costs required to implement them. Continual change in the equipment will be needed as this technology matures.

Capital requirements for a production facility are extremely difficult to judge. The most likely characteristic on which to judge this issue is the complexity of the envisioned technology process steps. Based on this, a ranking of the advanced technologies is shown in Table 4.8. The polycrystalline CdS and amorphous silicon options are the simpler of the technologies under consideration. The single-crystal options are by far the more complex in the number of steps and different processes required to produce the finished product. The polycrystalline silicon and GaAs are intermediate in this respect.

TABLE 4.8  
CAPITAL INVESTMENT RANKING  
PRODUCTION FACILITY

Ranking (Increasing Expense)	Technology Base
1      Lowest cost	Polycrystalline CdS
2	Amorphous silicon
3	Polycrystalline silicon
4	Polycrystalline GaAs
5	Single-crystal GaAs
6      Highest cost	Single-crystal CdS

#### VARIABLE COSTS RANKING

With sufficient volume, the capital investment in production facilities can be written off over a period of time and represent a relatively low portion of total costs. The other major costs associated with production, other than overhead, are direct variable costs. The variable costs are associated with volume levels and involve requirements for material and labor. In general, the more complex a manufacturing area, the more labor is needed and less potential for automation exists.

A ranking of the technology options under consideration as to their variable cost component of total costs is shown in Table 4.9. Because of the extremely low material content required in the amorphous silicon technology and the fact that the substrate material does not heavily influence film characteristics (this allows use of low-cost material), it is assumed that the material costs will be the lowest in the amorphous silicon option. The processing steps are few and simple in comparison also. Low material and labor costs should characterize this technology base.

At the opposite end of the spectrum is the single-crystal options that use very expensive materials, complex processing, and hold limited potential for automation. Here the labor and material costs will be relatively high for each peak watt of devices produced.

The remaining options fall between these two extremes. The polycrystalline gallium arsenide option is ranked higher in cost due to the cost of gallium. The polycrystalline CdS is ranked lower in cost than silicon due to less expensive substrate materials and the probable need for interface material layers in the polycrystalline silicon technology base.

TABLE 4.9  
VARIABLE COST OF MANUFACTURING RANKING

Ranking (Increasing Percent of Total Cost Due to Variable Costs)	Technology Base	Comments
1	Amorphous silicon	Low material costs Few steps High potential for automation ↓ High material costs Many steps Low potential for automation
2	Polycrystalline CdS	
3	Polycrystalline silicon	
4	Polycrystalline GaAs	
5	Single-crystal GaAs	
6	Single-crystal CdS	

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## 5. Industrialization Alternative Rankings

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### 5.1 INTRODUCTION

Some principal outgrowths of this study would be to:

- Assess the future potential of advanced photovoltaic technologies for industrialization
- Determine their state of readiness for a technology development program similar to the present-day single-crystal silicon project and the likely time frame within which they will become ready for such a program
- Recommend those advanced technologies for specialized government emphasis

The following definitions are used in connection with the above actions:

- Industrialization--the widespread industrial installation of low-cost manufacturing processes and techniques to produce photovoltaic-based products.
- Technology development program--a government-supported spectrum of programs, contracts, and policies directed at optimizing the performance and cost characteristics of a photovoltaic technology base. This is in contrast to proving feasibility of the technology base in the laboratory environment and independent of efforts to encourage industrialization.
- Laboratory R&D programs--programs supported by government funding that are directed at demonstrating feasibility, reproducibility, and stability of a photovoltaic technology base in the laboratory environment.
- Government emphasis--assignment of funds and resources emphasizing the parallel pursuit of selected technologies, all of which are not necessarily at the same level of maturity.

In the following section, the present-day technical assessments and the future characteristics of matured technology bases will be used to establish industrialization rankings and the judged maturity development pace of the advanced photovoltaic technologies. This then leads to a set of recommended government actions.

## 5.2 RANKING OF TECHNOLOGY BASES

On the assumption that all of the advanced photovoltaic technologies under consideration in this report were fully developed, the question arises as to which of these technologies has those characteristics that would represent good prospects for industrialization. Such an assessment of the various technology options is shown in Table 5.1.

TABLE 5.1  
FUTURE POTENTIAL FOR INDUSTRIALIZATION\*

Potential	Technology Base	Comments
High	Polycrystalline silicon Polycrystalline CdS Amorphous silicon	These all represent very low-cost potentials; if performance and reliability can be demonstrated, then industrialization is highly possible.
Possible but with difficulty	Single-crystal GaAs	Widespread industrialization will be limited due to perceived commercial application limitations in predictable future (maximum of next ten years); will depend on degree of identified concentrator application areas and their potential.
Low	Polycrystalline GaAs	Even if excellent performance and reliability characteristics are demonstrated, cost-performance trade-offs will restrict industrialization.

\*Assumes: Performance characteristics can be reproducibly demonstrated; reliability can be established.

It is seen that all but polycrystalline GaAs do have the potential for industrialization. The lack of sufficient cost/performance trade-offs of polycrystalline GaAs (compared to other thin-film options) reduce the likelihood of widespread acceptance of this technology. Single-crystal GaAs has excellent performance characteristics and conceivable low-cost concentrator system prospects, but it will be limited by the perceived commercial marketplace for such products. If the perceived market can be significantly increased or its availability can be brought closer to the near term, then prospects for single-crystal GaAs could be significantly improved.

The primary prospects for industrialization, once the technology is fully developed, are the thin-film silicon and CdS technologies. These all represent low-cost, continuous-process technologies with reasonable efficiency of conversion (10 to 18 percent) prospects. Availability of material and long-term reliability characteristics could be the ultimate deciding issues among these alternatives rather than performance parameters.

The basic assumption in the above evaluations was that technology development and maturity levels were well-established and comparable. Since these technologies are not beyond the laboratory stage, the issue of how long it will be before these technologies are sufficiently developed to justify a technology development program must be addressed. The minimum time required to prepare these technologies for such programs is addressed in Table 5.2.

TABLE 5.2  
MINIMUM TIME REQUIRED BEFORE TECHNOLOGY COULD BE READY\*  
FOR TECHNOLOGY DEVELOPMENT PROGRAM

Minimum Time Required	Technology Base	Comment
<2 years	Single-crystal GaAs	Close to full potential now
2-5 Years	Polycrystalline CdS	Reliability problems would have to be overcome
>5 Years	Polycrystalline silicon Polycrystalline GaAs Amorphous silicon	In general, reliability, reproducibility, costs, and performance significantly below estimated potential; lack of sufficient understanding, not sufficiently developed to justify technology development program presently.

\*Refers to reproducibly demonstrating performance characteristics.

Single-crystal GaAs is close to full potential now and is ready to move into the pilot production stage at a few industrial locations. This technology could be readied for a technology development program in one to two years. In effect, the fundamentals of such a program already exist through the present efforts of the Sandia Laboratories.

Polycrystalline CdS is the next most likely candidate to be readied for a technology development program. The major problems of cell stability and long-term reliability are severe and could delay its ultimate industrialization for many years. In comparison to single-crystal GaAs, it is far behind in reproducibility, device understanding, and optimization.

The lowest likelihood of laboratory success in the near term (less than five years) is associated with polycrystalline silicon, amorphous silicon, and polycrystalline GaAs. In general, these technologies are characterized as being significantly below their expected future potential. They are still in the early development stage of attempting to prove feasibility and reproducibility. Prospects of them developing rapidly under present-day levels of effort are very limited. A technology breakthrough or a sudden resolution of critical barriers could, however, alter the assessment of these longer-range technologies significantly.

### 5.3 RECOMMENDED GOVERNMENT ACTION

The recommended government action on the advanced technologies is shown in Table 5.3. It is recommended that single-crystal GaAs be pursued through a vigorous technology development program to ensure its readiness for industrialization when the commercial market conditions become more favorable.

TABLE 5.3  
RECOMMENDATIONS FOR GOVERNMENT DEVELOPMENT EMPHASIS

Recommendation	Technology Base (Recommended Government Action)	Comments
Recommended for government emphasis	Single-crystal GaAs (technology develop- ment program)	Most mature; offers best potential in concentrator applications
	Polycrystalline silicon (contracts to support laboratory feasibility demonstrations)	Best available thin-film alternative to single-crystal sheet or ribbon for low-cost, continuous-flow processing; performance potential comparable to polycrystalline CdS without potential reliability problems
	Amorphous silicon (contracts to support laboratory feasibility demonstrations)	Best long-term potential for costs; excellent material availability; technology under- standing applicable to many other application areas and materials
Possible as alternative to polycrystalline silicon	Polycrystalline CdS (contracts to support laboratory feasibility demonstrations)	Best presently-developed thin- film technology base; proper packaging could overcome reliability problems; material availability not as good as silicon; however, could offer quicker thin-film solution than polycrystalline silicon.
Not recommended as primary governmental emphasis	Polycrystalline GaAs Single-crystal CdS	Continue investigations at laboratory level for pursuit of material and basic mechanism studies



Polycrystalline silicon should be supported through development contracts to assist in demonstrating laboratory feasibility. This technology represents the best overall thin-film alternative to single-crystal sheet or ribbon for low-cost, continuous-flow processing. The performance potential is comparable to polycrystalline CdS without the severe stability and long-term reliability hazards.

A possible alternative to polycrystalline silicon is the polycrystalline CdS due to its somewhat more mature state of being. If an alternative to single-crystal silicon sheet or ribbon is needed in the mid-1980s, polycrystalline CdS may offer a quicker route than polycrystalline silicon.

The amorphous silicon technology should receive high emphasis in support of laboratory efforts to demonstrate feasibility. This technology represents the best long-term prospect in all the advanced technologies. Its many attributes were highlighted in Table 4.2. It has in its favor prospects for low cost, excellent material availability, and comparable performance characteristics. An understanding of amorphous silicon will lead to an understanding of amorphous structures in general, which will have positive effects in other application areas and materials.

Pursuit of polycrystalline GaAs, single-crystal CdS, and many of the other advanced technologies shown in Section 3.8 should be at a reduced emphasis. These technology bases should not be totally ignored, however. Buried within them may be a technology base having superior prospects beyond those emphasized in this report.

It is assumed, however, that limited funds, manpower, and other resources will not permit heavy emphasis on all these options simultaneously. For that reason, the recommended high-emphasis technologies were selected and a low-level, but continuing, effort should be directed at the remaining options.

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## 6. Methodology

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### 6.1 INTRODUCTION

This study was driven by the perceived need to evaluate and compare the potentials and requirements of advanced photovoltaic technologies that are still in their early developmental stages. Establishment of such comparative information will be needed in the near future when government agencies attempt to select and develop supportive programs for the industrialization of future photovoltaic technologies.

The foundation and base position that allowed Gnostic Concepts to launch such an investigation was based upon:

- Prior work in the field of photovoltaics
- Staff of qualified personnel experienced in the evaluation and comparison of technical options
- Relationship with research organizations within industry, government, and academic institutions

One of the major functions of Gnostic Concepts, Inc. is to provide services in business and governmental areas where leading-edge technologies are inducing change and impacting broad sectors of the economy. An extensive background in the collection of technical data permeates all the major activities of the company.

The company has concentrated on those areas where rapidly changing technical or economic environments create the need for in-depth analysis. Analytical tools such as field surveying, data collection, and computerized analysis support the company's activities.

## 6.2 STUDY DEVELOPMENT

### RESEARCH OF GNOSTIC CONCEPTS, INC. MATERIALS AND OTHER LITERATURE

Over the years, many studies have been performed at Gnostic Concepts that involved many of the companies and organizations presently active in the development of photovoltaic technologies. These related studies add great insight and a foundation upon which to base further extensive interviews specifically designed for this study. These related studies also give insight into the development trends within the high-technology-based industries. Because of this background, the technology development trends within the photovoltaic industry could better be focused and viewed from a broad number of perspectives. A significant and broadly-based comparison background was thus available within the company that assisted in focusing the field interviews and analyses required.

A search of the publicly available written material was also performed. This included annual reports, government-published data, technical journals, pertinent industry journals, news releases, and public speeches given by company executives.

Due to the many technical studies performed in the electronic industry, Gnostic Concepts has available an extensive set of interviews with company executives and many corporate technical personnel. Through these previous interviews, the necessary relationships had already been established in many cases that allowed the rapid and efficient execution of the needed interview programs for this specific study. These new interviews, along with the previous interview material, formed a significant portion of the basis for the results and conclusions of this study.

### FIELD SURVEY

The gathering of the basic information concerning the technology assessments was collected through an extensive field interview program directed at:

- Industrial organizations
- University research laboratories
- Government research laboratories

The industrial base field survey work included a cross-section of various industries, such as the petrochemical industry, electronic firms, equipment firms, materials companies, and conglomerates. The interviews covered primarily the technical activities of each organization, including the government and university research laboratories.

## REPORT PREPARATION

Before any extensive field work was begun, there were planning sessions with JPL personnel. The objective of these planning sessions was to establish very specific criteria for the content of the report. A detailed outline of procedures was established that indicated the type of companies to be interviewed, the spectrum of data to be collected, the expected content, delivery date of all pertinent documents to JPL, and a thorough review of the intent of the study.

To pace the program and to provide interim milestone checkpoints on the progress of the report, an interim report and final report outline were issued. These reports allowed for the interaction of JPL and Gnostic Concepts personnel to review the status, content, and quality of the material to be presented.

Once the fundamental information was gathered on the required technologies, activities within the project were then directed at the establishment of a comparative framework by which the technologies could be assessed. The results of the literature search, the interview program, available data from related studies and previous interviews, and the interfacing with JPL personnel have all culminated in the issuing of this report.

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## 7. Glossary

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### Amorphous structure

A crystalline structure having no repeatable or periodic organization of its atomic elements.

### Capital investment

Those monies invested in equipment and associated facilities, including initial installation costs.

### Dopant

Material introduced at the atomic level into the crystalline structure of a base material to alter the electrical properties of the base material.

### Efficiency

The ratio of power output of a photovoltaic cell to the incident power from the sun or simulated sun sources under specified standard insolation conditions.

### Epitaxial process

A method of deposition of a crystalline semiconductor film on a substrate of similar or identical crystal structure, usually at elevated temperatures.

### Fill factor (FF)

The ratio of maximum power output to the product of the open circuit voltage and the short circuit current.

### Grain boundary

The interface between two single-crystal-oriented segments of a polycrystalline structure.

### Hermetic

Being impervious to external influences. Typically associated with the sealing of a package such that oxygen, moisture, and other outside environments cannot enter the package.

### JPL

Jet Propulsion Laboratory.

Open circuit voltage ( $V_{OC}$ )

That voltage produced by a photovoltaic cell with no load applied when exposed to standard insolation conditions.

Polycrystalline structure

A material having a crystalline structure composed of randomly oriented segments of single-crystal-oriented lattice structure.

Short circuit current density ( $J_{SC}$ )

That current produced per unit area of the photovoltaic cell with a short circuit load applied when cell is exposed to standard insolation conditions.

Silane ( $SiH_4$ )

A gaseous by-product resulting from the distillation process used to decompose ferro- or metallurgical-grade silicon. It is used for the generation of dielectric films in the semiconductor industry and the formation of amorphous silicon photovoltaic structures.

Single-crystal structure

A material having a crystalline structure such that a repeatable or periodic molecular pattern exists in all three dimensions.

Variable costs

Those costs of manufacturing associated with the variation in levels of production, i.e., labor, material, consumables.